THE LAND OF CLOUDS REVISITED

The Biodiversity and Ecology of the Eungella Rainforests

Edited by Roger Kitching

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VOLUME 125 | 2020

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Environmental Futures
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CATCHMENTS

The Society thanks the anonymous referees who reviewed papers submitted for publication in this Special Issue of the *Proceedings*. Special thanks are extended to Griffith University – Environmental Futures Research Institute, Reef Catchments natural resource management group, and an anonymous philanthropist for contributing to the costs of typesetting and printing this volume.

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FOREWORD

The Royal Society of Queensland and its predecessor the Queensland Philosophical Society have been publishing the results of scientific and natural history investigations since 1859. From 1884, this has been primarily through a nearly annual issue of the *Proceedings*, supplemented from time to time with Special Issues on specific themes. This volume stands in that proud tradition.

When Professor Roger Kitching of Griffith University approached the Society with an offer to assemble scholarly papers resulting primarily from fieldwork in the Eungella rainforests, the Society's Council did not hesitate to endorse the proposal. We are delighted that Professor Kitching has been able to fulfil his commitment and bring this fine collection of papers to maturity.

As I write this foreword, a debate – or perhaps more accurately, a controversy – is alive over the credibility of the science associated with the condition of the Great Barrier Reef. A faction of politics is claiming that the science is ambiguous, that the institutions established to conduct and disseminate research have been biased and, perhaps worse, that a third or more of scholarly articles in the sciences generally are flawed and unreliable.

Without denying the legitimacy of a credibility problem in some corners of scientific research, particularly commercially orientated research, an excellent retort to these contemporary attacks on scientific integrity was provided by Dr Alan Finkel, Chief Scientist of Australia, in the John O'Hagan Lecture on 20 November 2018 (John O'Hagan is an Honorary Life Member of The Royal Society of Queensland):

> *Probably the most credible journals are the journals of small societies, edited by volunteer scientists working through the night.*

This status eminently describes the *Proceedings of The Royal Society of Queensland*!

Any person who has edited a journal in the natural sciences can attest to the painstaking attention that authors and reviewers and the others involved give to their roles, by poring over manuscripts word by word, fixing typos, clarifying ambiguities, hunting for mistakes. The result is typically as reliable as human cognition can achieve.

The Society is immensely grateful for financial contributions from the Environmental Futures Research Institute, Griffith University, through its director Professor Zhihong Xu, the Reef Catchments natural resource management group and an anonymous donor towards the publication of this volume. These donations have enabled the Society to proceed to print publication, giving the work a tangible presence and long archival life. The support from these bodies is evidence that scholarship is valued and that the labours of the authors, reviewers and Editor have resulted in a permanent addition to human knowledge.

Dr Ross Hynes
President

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GUEST EDITORIAL

In 2010 I delivered a talk to the annual meeting of Environmental Officers from local government agencies held at Surfers Paradise. I described the extensive biodiversity survey work we completed in Lamington National Park and at Mt Lewis in the Wet Tropics of Queensland. I ended by lamenting that detailed, elevationally partitioned surveys of the Eungella massif, more or less midway between our two earlier locations and known to be of great biological interest, had not been carried out and would not happen unless substantial funding was provided from somewhere. This was a sort of throw-away line, I'm afraid, with the perennial research scientist's appeal for more funding, please.

Immediately after the talk, and to my surprise and delight, I was approached at the podium by Dan McKinlay and Councillor Wendy Cameron from the Mackay Regional Council with the suggestion that we begin a conversation about how the suggested Eungella work might be achieved and funded. And that was how the 2012–2014 Eungella Biodiversity Survey (EBS) began. The full details and funding arrangements are described and acknowledged in Louise Ashton's contribution in this volume. The greater part of the funding came jointly from the Mackay Regional Council, with matching funds from the Queensland Government as part of a larger grant under the Queensland-Chinese Academy of Sciences Joint Biotechnology Programme. Drs Aki Nakamura and Louise Ashton were employed to run the survey.

Considerably later, we were faced with the challenge of making our many results available to the widest possible audience. Some of our Eungella data had already been presented, usually as part of comparative analyses, in other journals. There remained, though, a large body of detailed information that still sought a home and, ideally, a shared home in which adjacent scientific results remained adjacent upon publication. I approached Geoff Edwards, then President of The Royal Society of Queensland, about dedicating a Special Issue of the *Proceedings* for this purpose. He and the Council of the day welcomed this suggestion, some outside funding was sought and gained, and the present volume is the outcome.

As Editor I took the opportunity to invite additional papers, beyond the initial scope of the EBS, to expand the coverage of the Special Issue. The recruiting of contributions, awaiting the last submissions, getting contributions refereed, and then going through several stages of the editorial process took time and effort and would not have been achieved without considerable assistance. As referees I especially thank Daryl Barnes, Chris Burwell, Frank Kohler, Bert Orr and Geoff Tracey. Geoff Edwards encouraged, promoted and ultimately approved the whole process, for which I am very grateful. Finally, I thank Darryl Nixon of Sunset Publishing Services for his proofing and typesetting skills, and for seeing the drafts through to their elegant final form.

Roger Kitching

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EUNGELLA – THE LAND OF CLOUDS REVISITED

KITCHING, R. L.[1]

The rainforests of the Eungella massif are well known as centres of endemism and species richness. The name Eungella was adopted from local indigenous languages by the first European residents. First visited by professional biologists in 1922, the region has attracted scientific attention ever since. The Eungella Biodiversity Study in 2012–2014 attempted to place the many endemics into their wider ecological context. This compilation presents many of the results of that survey plus selected other contributions on the biology and ecology of this important conservation area.

Keywords: Eungella, Queensland, biodiversity

[1] *Environmental Futures Research Institute, Griffith University, Nathan, Queensland, Australia*

The Clarke Range looms, mist shrouded and challenging, about 60 kilometres west of Mackay up the valley of the Pioneer River and, beyond, the unimaginatively named Cattle Creek. It is not clear who were the first Europeans to actually set boots upon the ground in what are now the rainforested tracts of Eungella National Park. Certainly Captain John Mackay and his party must have seen the distant shadows of the forested hills to the north-west when they encountered the junction of what is now the Pioneer (originally the Mackay) and Cattle Creek on the 21st of May, 1860. The party continued on down the Pioneer to be the first to reach the Mackay District from the landward side. Several earlier maritime expeditions had at least seen the coastal country from the sea. The subsequent development of the region as cattle and sugar country was rapid, with the first settlers arriving just two years after Captain Mackay's discovery. By 1866 the town of Port Mackay had a network of streets and buildings including stores and pubs, of varying repute, as well as dwellings on the south bank of the Pioneer. David Hay Dalrymple (one of the many complexly related Dalrymples and Dalrymple-Hays in the early history of the region) was the first mayor of Mackay elected in 1870, just a year after the town council was proclaimed.

The Eungella massif sits inland from Mackay in the hinterland of the Pioneer River. An area of great contrasts, it contains a green jewel of moist rainforest surrounded by brigalow scrublands.

Eungella is generally supposed to mean 'Land of Clouds' in the now virtually extinct Birri (also known as Garingbal) or Wiri languages. According to the Indigenous Languages Map hosted by the State Library of Queensland's *Indigenous Languages* website[a], the area that is now Eungella National Park and its surrounds was the traditional home of the Birri and Wiri peoples. The area that is now the Mackay region on the coast was the home of the Yuwi people.

The lease on what became the Eungella Station was first taken up in 1880 by the Barker Brothers, and *The Queenslander* of 24 January 1880 records the arrival of a stud bull for "Mr Barker of Eungella". There is no mention in any newspaper archive of the word 'Eungella' before 1880. Presumably the local name was adopted by the Barkers when the station was established. The subsequent story of the station is recorded in a transcript of a local history recording of the current proprietor, Darryl McEvoy, made by Del Cunningham in 2009.[b] The transcript contains no mention of the indigenous people of the area. Subsequently, in or about 1887, gold was discovered in the area and a mini-goldrush ensued[c] in what was termed the 'Eungella Goldfield'. So the name 'Eungella' was clearly entrenched well before any biological interest was shown in the region.

The area first came to the attention of biologists when it was visited by the Assistant (Queensland)

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[a] Accessed at https://www.slq.qld.gov.au/discover/aboriginal-and-torres-strait-islander-cultures-and-stories/languages on 23 July 2019.

[b] Transcript available on http://history.eungella.com.au/Personal%20Accounts/files/Beef%20-%20Droving%20and%20the%20Dam.pdf (accessed 23 July 2019).

[c] https://trove.nla.gov.au/newspaper/article/84113264 (accessed 23 July 2019).

Government Botanist, William D. Francis, in 1922 (Francis, 1927). On that look-and-see visit, Francis compiled a list of trees from the region, noting in particular the abundance of red cedars and the unique admixture of subtropical and tropical species. Francis marvelled at the rainforest of the area, which he had accessed first by rail up the Pioneer Valley and, thence, by foot (or horseback) up the range to the area 'above Netherdale'. He also collected material which led to the description of perhaps the first Eungella species – the tree *Cryptocarya corrugata* (White & Francis, 1926) – although its range has been shown subsequently to include some of the more northerly mountains as well.

Since Francis's visit the area has, over time, attracted the attention of biologists and became renowned as a centre for endemism. Since its first, partial, gazettal as a National Park in 1936, the area has been visited by ever increasing numbers of specialists attracted by the isolated nature of this large area of rainforest and the likelihood of hitherto undescribed endemic species being found there. Perhaps its best known endemic is the Eungella honeyeater, *Bolemoreus hindwoodi*, which was formally distinguished from the bridled honeyeater (*B. frenatus*) as recently as 1983 (originally described by Longmore & Boles, 1983, as *Meliphaga hindwoodi*). Perhaps more remarkable among vertebrate endemics was the Northern gastric brooding frog (*Rheobatrachus vitellinus*), described by Mahoney, Tyler & Davies in 1984, when its extraordinary brooding behaviour was recorded. The species is now classed as extinct, no individuals having been seen since 1985 – a mere 12 months after the species' formal description. A further local endemic frog, the Eungella day frog (*Taudactylus engellensis*) occurred in the same streams and, for a time, was thought to have disappeared at the same time as the *Rheobatrachus* species. More recently, small remnant populations have been found. An additional species of frog and a number of species of reptile are also endemic to the area (Stuart-Fox *et al*., 2001; Sadler *et al*., 2005; Hoser, 2014).

These charismatic vertebrates, however, are but the tip of the iceberg. A whole genus of pselaphid beetles bears the name *Eungella*. In addition, no fewer than 23 invertebrates bear the specific name *eungella*, and a further 15 are designated *eungellae*. These range from mites to millipedes, stoneflies to moths and, with just five exceptions, all are recorded so far only from the Eungella area. There are probably many more unique species whose describers gave them a name other than the readily searched-for *eungella* or *eungellae*[d] eponyms.

As part of the successful Eungella Biodiversity Study carried out in 2012–14, many taxa were sampled systematically over an elevational gradient from 200 m to 1200 m above sea level (Ashton *et al*., this volume). This survey was unique in many ways but perhaps most notably because a substantial proportion of the fauna and flora of the study sites were targeted (rather than only endemics). The detailed scientific results are presented in this special issue of the *Proceedings of The Royal Society of Queensland*. In addition to a general description of the survey (including the vegetation), this issue includes detailed results on the birds, ants, dragonflies, pyraloid moths and gastropod molluscs surveyed. In addition I have invited further contributions from researchers with special interests in Eungella, even though they were not participants in the Eungella Biodiversity Survey. Accordingly, we have a contribution summarizing the history of the National Park, two contributions on the frogs of the region plus a thoughtful essay on the dynamic effects of recent fire events on the integrity of the Park and its invaluable forests.

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[d] Searches for *eungella* and *eungellae* carried out in the *Atlas of Living Australia* https://www.ala.org.au/mapping-and-analysis/. Accessed 23 July 2019.

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THE DEVELOPMENT OF NATIONAL PARKS IN THE EUNGELLA REGION

OGILVIE, P.[1]

In the first half of the 20th century, the declaration of areas as national parks had much more to do with attracting tourists than with protecting natural resources. Consequently, the early parks were frequently relatively small areas. Initially, Eungella was no different. The first park in 1936 was approximately 405 hectares. That trend was clearly disregarded only five years later when an area of 48,295 hectares was declared as national park over significant samples of rainforest and eucalypt forest along the Clarke Range. It was the largest national park in Queensland to that date, a distinction it held for more than a quarter of a century. Archival records in government files clearly support the contention that nature conservation, particularly the protection of rainforest, was an important factor driving the declaration of Eungella National Park, one of Queensland's most important protected areas.

Keywords: Eungella, National Park, history

[1] *457 Upper Brookfield Road, Upper Brookfield, Queensland, Australia*

NATIONAL PARK ESTABLISHMENT IN QUEENSLAND

The framework for the establishment of a State-wide system of national parks in Queensland dates back to 1906 when *The State Forests and National Parks Act of 1906* was passed by the Queensland Parliament. It was a significant statute in a national, as well as State, context in that it was the very first Act in Australia to provide for the establishment and administration of national parks across a whole State jurisdiction.

The other States utilised reserve-making powers in other Acts, particularly the relevant Land Act, to declare reserves for national park, or passed specific acts for individual parks. In most cases, however, these weren't administered by any central authority and were often placed in the hands of government-appointed boards of trustees. By way of example, New South Wales, which declared the first national park in Australia in 1879, did not have jurisdiction-wide legislation for the management of national parks until 1967.

In addition, the national park reserve status in other jurisdictions could, in most instances, be easily revoked by regulation. In Queensland, once a national park was declared under the 1906 statute, it could be revoked only by an Act of Parliament. For the early 1900s, when nature conservation wasn't a major consideration in establishing national parks, this level of legislative protection suggests considerable foresight on the part of certain bureaucrats and politicians.

To illustrate that point, section 4 of the Act read (in part) as follows: "From and after the Proclamation of a State Forest or National Park under this Act, no such State Forest or any part thereof or National Park or any part thereof shall be sold or otherwise alienated in fee-simple or for any less estate, except under the authority of an Act of Parliament."

The State Forests and National Parks Act of 1906 was administered by the Sub-Department of Forestry, which was a semi-autonomous component of the Department of Lands until it gained full departmental status in 1957, and that led to the 1906 Act being replaced by the *Forestry Act 1959*.

This background to national park establishment and administration provides a framework for understanding the process for declaring national parks in Queensland and the reason why a large proportion of the early parks came from land set aside, initially, as timber reserves and State forests. This is particularly relevant to the establishment of Eungella National Park where the bulk of the land dedicated as national park had originally been set aside for forestry purposes.

THE IMPETUS FOR ESTABLISHING A NATIONAL PARK

The impetus for the establishment of a national park in the Eungella area derived from a desire by the Mackay community to attract more people to the region, coupled with the Government's desire to identify areas for settlement, forestry and agriculture.

The national park file (Queensland State Archives R.573) contains a 6 February 1959 memorandum outlining some of the gazettal history. It states that the idea of a national park at Eungella arose in 1932 when a special committee comprising representatives of the Departments of Lands, Forestry and Agriculture, together with a director of the Mackay Butter Factory, was appointed by the Government to investigate, in the Eungella district, (a) areas best suited for settlement, (b) areas best reserved for forestry, and (c) areas that should be retained for national parks and scenic purposes. In relation to the latter, the committee considered it "essential that a compact area containing places of definite scenic value and sufficient in extent to preserve the jungle in its primeval state should be reserved".

The memorandum also points out that the report was not acted on for some years, during which roads were constructed and settlement progressed.

THE FIRST NATIONAL PARK

The first national park to be declared in the Eungella area was gazetted on 7 March 1936 (*Queensland Government Gazette*, page 938). It was a reasonably small area of "about 1,000 acres" (405 ha) along the banks of the Broken River. At that time, and up until 1992, when certain sections of the *Nature Conservation Act 1992* came into force, all national parks were assigned a reserve number. That number related to the parish(s) in which the park was located and placed them in a context with other public land, most of which was set aside under the Land Act. In the absence of a specific name, this small park was known as R.21 Crediton.

Although no documentation explaining the stimulus for this declaration has been unearthed, it is likely to have derived from the aforementioned special committee as well as the same source that lobbied two years later for further declarations. A letter dated 10 October 1938 to the Premier, the Hon. W. Forgan Smith, from the Secretary of the Mackay Chamber of Commerce was headed "EUNGELLA NATIONAL PARK" and stated, *inter alia*: "Further to prior correspondence in this matter we have to advise that the Chamber undertook an aerial survey of the area designed for reservation as a National Park, in particular reserve No. 97." The letter sought the Government's commitment to the gazettal of the national park and also to "the building of trails and tracks, particularly to the summit of Mt Dalrymple". The title of their letter is one of the first references to the name Eungella National Park, though it may have been used in earlier unsighted correspondence.

With reasonable road access now available up and over the Clarke Range, the Chamber was very active in attracting tourism to the region. National parks were seen as tourist drawcards, particularly if facilities such as picnic areas, camping facilities and walking tracks were supplied. Being administered by Forestry meant that a workforce with the necessary skills for such facilities was generally available if production forestry activities were being undertaken nearby.

THE SECOND NATIONAL PARK

Following representations by the Mackay Chamber of Commerce and a reasonably new public organisation (the National Parks Association of Queensland) established in 1930 to advocate for new national parks, the second national park in the Eungella area was dedicated in 1941.

The President of the National Parks Association, Mr Romeo Lahey, wrote to the Minister for Public Lands, Mr P. Pease, on 12 February 1940 requesting that he give favourable consideration to the reservation as a national park of "a large area of the Eungella Range". He refers to three contiguous areas of differing characteristics being included: "1. The area along the upper waters of Broken River adjoining the existing National Park; 2. The area on the eastern face of the Eungella Range down to the existing selections of coastal plain; and, 3. The area on the western fall of Eungella Range extending to the western edge of what is known locally as Dick's Tableland." In relation to the first area, the letter refers to the swimming pool and "the adjoining 'bald' or natural area of grass surrounded by scrub, as this seems to be the only one of its kind in the district". The 'balds' of Bunya Mountains National Park were well known at that time.

In relation to the second area, the letter refers to the rainforest, gorges and waterfalls, as well as to the necessity to protect the area from fire to prevent it becoming a mass of lantana, as had already happened on the side of the Barron Gorge. The third area includes rainforest and eucalypt forest, plus the comment: "the evidence of bears being particularly pleasing".

Romeo Lahey was one of the two prime movers in the establishment of Lamington National Park in 1915, taking what was a small original proposal and converting it into a substantial and well-considered proposal of 22,500 acres (Ogilvie, 2006). He was also the founder (in 1930) and first president of the National Parks Association of Queensland. Lahey had undertaken an inspection of the Eungella area prior to his letter.

The Premier, William Forgan Smith, had written on 15 March 1940 to the then Minister for Public Lands, Mr P. Pease, referring to his recent visit to Mackay when he was approached "in regard to the reservation of a large area in the Eungella Range as a National Park". He goes on to say, "I recommend that the necessary action be taken at an early date to gazette a suitable area as a National Park."

The reference to Eungella Range is interesting. It undoubtedly refers to what is now known as Clarke Range. There is little doubt the range was named after the Reverend Branwhite Clarke, a Sydney-based clergyman and geologist who has been referred to as 'the father of Australian geology'. Clarke was a friend of Ludwig Leichhardt, and it was Leichhardt who, on his 1844–45 expedition to Port Essington, named a branch of the Burdekin River in Queensland after Clarke. Leichhardt's journal entry for 22 April 1844 (Leichhardt, 1847) placed him at 19°12′S and states: "I called the south-west branch the 'Clarke', in compliment to the Rev. W. B. Clarke of Paramatta, who has been, and is still, most arduously labouring to elucidate the meteorology and the geology of this part of the world."

Clarke, in a letter to his mother in England (Grainer, 1982), refers to Leichhardt's expedition and tells her that "he has paid me the compliment of naming a river after me which you will see on the next map of New Holland. It runs into the Burdekin which enters the sea on the east coast near Cape Upstart." That still doesn't explain the naming of the range which is the headwater for streams that ultimately join the Burdekin.

In a letter dated 27 September 1940, the then Minister for Lands, E. J. Walsh, advised the Premier, Mr Forgan Smith, that the Director of Forests and the Surveyor-General had collaborated and recommended an "area of about 120,000 acres on the Clarke Range and in the vicinity thereof be set apart for the purpose of a National Park".

The area included all of the features highlighted by the Chamber of Commerce – Finch Hatton Gorge, Massey Gorge and Mt Dalrymple – and was extracted primarily from previous Timber Reserves, some of which had been gazetted as far back as 1901.

A memorandum of 26 July 1940 from the Director of Forests, Vic Grenning, to the Chairman, Land Administration Commission, outlined the national park proposal and referred to its tourism and conservation potential. The memo includes the following:

> After considering reports furnished by Forest Officers from their knowledge of the locality, I recommend that the area shown on attached map be reserved for National Park.
>
> This will embrace a wide variety of scenery, including the commanding heights and ramparts of Mt Dalrymple and adjacent mountains, the palm and vine jungles of the eastern slopes and the great gorges and eucalypt forests of the western fall of the Clarke Range, including Dick's Tableland.
>
> The area so recommended embraces about 109,000 acres and includes parts of Timber Reserves 6 and Crown lands, parishes of Cauley and Gamma, 394 Lacy and 97 Pelion.
>
> It should be understood that no intensive investigation has been made; to do so would be costly and require a considerable amount of time.
>
> At a later date sections of these timber reserves will be subjected to closer examination and steps could then be taken, if necessary, to reserve as National Parks any further areas of special scenic value revealed by such investigations.

This time there was a serious area of land involved – 119,340 acres (48,295 ha) to be precise. The proclamation of the national park was published in the *Queensland Government Gazette* of 25 January 1941 (pages 173–174). It extended across two counties (Carlisle and Hillalong) and four parishes (Lacy, Mia Mia, Pelion and Gamma). It was allocated two reserve numbers: R.573 and R.44. Part of its south-western boundary was adjacent to National Park R.21 Crediton on Broken River.

It was the largest national park in Queensland at the time, surpassing Bellenden Ker National Park (declared 1921; 79,000 acres) and Hinchinbrook Island National Park (declared 1932; 96,700 acres).

There were some strong local objections to the national park by people who saw it restricting their capacity to carry out timber extraction. This included requests that permission be granted to remove timber from the park.

FOUR MORE NATIONAL PARKS

The January 1941 declaration seems to have triggered four more park gazettals in the Eungella region less than six months later. Four new national parks were published in the *Queensland Government Gazette* of 19 July 1941 (page 103).

Two of those parks were actually assigned a name in the *Gazette* notice – Broken River National Park. Both of them were contiguous with the first park, R.21 Crediton. They were modest areas, 615 acres and 240 acres respectively, exclusive of any roads within the defined boundaries. The third park was tiny and involved a single portion (portion 26) with an area of 11 acres 2 roods.

The fourth park (R.30) was even smaller (portion 53) with an area of 10 acres 2 roods. It was also assigned a name in the *Gazette* – Long Creek National Park.

THREE MORE PARKS

A seventh national park (R.51) was published in the *Gazette* of 13 March 1948 (page 826). It was also a single portion (82 Parish of Eungella) with an area of 4 acres 8 perches, having been a special lease forfeited for non-payment of rent and was located across the road from the big park, R.573. Another single-portion park (R.55) was gazetted on 11 March 1950 – portion 69, of 9 acres 1 rood 4 perches. And on 26 August 1950, the *Gazette* (page 1166) announced the declaration of a national park (R.52) of 200 acres over land that was a Scenic Reserve.

The same gazettal notice of 26 August 1950 also announced the inclusion of nine Scenic Reserves (R.20, R.46, R.47, R.33, R.34, R.35, R.28, R.29 and R.40) into the large Eungella National Park (R.573), resulting in an additional 1020 acres. The total area of the park was now 120,360 acres (48,708 ha).

AMALGAMATING THE VARIOUS NATIONAL PARKS

A 6 February 1959 memorandum on the R.573 file outlines some of the gazettal history and highlights certain components of the park considered to be relevant to its establishment. The following quotes are extracted from that memo:

> The terrain of this National Park is generally very rugged and is intersected by the Clarke Range which has a height from 3000–4000 feet. The eastern fall of the range is extremely rough being interspersed with numerous peaks. Some of these are Mt. Dalrymple, 4190 feet, Mt. William, 4082 feet, Mt. David, 3990 feet, Bull Mountain, 2770 feet, Mt. Omega, 2750 feet, Mt. Margaret, 2020 feet, Mt. Consuelo, 1870 feet, Mt Lilian, 1680 feet. The western fall comprises Dick's Tableland, which is also very rugged country, falling away in the south to a sheer drop of 1000 feet to the Massey Gorge. In this section there is situated a set of waterfalls 300–400 feet deep.
>
> The nature of the country lends itself to magnificent panoramic views of the surrounding countryside and to the islands dotted off the coastline. It has been described by a former Governor, Sir Leslie Orme Wilson, as one of the magnificent views in the world whilst a former Premier, Mr W. Forgan Smith, was led to remark that the scenic beauty of Eungella makes it one of the most valuable tourist areas in the State.

On 9 March 1961, the Executive Council decreed by Order in Council that "Scenic Areas R.55, R.51, R.30, in the parish of Eungella, National Park R.57, in the parish of Crediton, National Park R.44, in the parishes of Gamma and Eungella, shall be, and are hereby amalgamated with the existing contiguous National Park R.573, parishes of Lacy, Mia Mia and Pelion". It was formally designated as National Park R.573 Counties of Carlisle and Hillalong, parishes of Lacy, Pelion, Mia Mia, Eungella and Gamma, with an area of "about 122,600 acres" (49,614.5 ha).

DISCUSSION

The early establishment of Eungella National Park involved the declaration of a number of small areas that were ultimately amalgamated with the large area set aside in 1941. While the initial stimulus for establishing such a park had a strong emphasis on attracting visitors to the Mackay region, there was also a clear and commendable intent to preserve substantial samples of the rainforests and eucalypt forests residing on and adjacent to the Clarke Range.

The area of land involved clearly supports the latter contention. No earlier national park involved anywhere near such an area of land. The recreational uses envisaged at the time did not need that sort of area. It is a tribute to the foresight of certain officers in the Forestry Sub-Department that such an important area was given national park status which, as mentioned earlier, had much stronger legal protection than it has today.

The park's value to the tourist and to the protection of natural resources was highlighted in the October 1948 issue of the *Road Ahead*, the RACQ magazine. An article entitled *Eungella National Park* included the following comments:

> The reservation of this area during the war years did not receive the widespread notice it deserved, although local interest had been drawn to the necessity for preserving the magnificent area concerned.

> This mountainous area which includes one of the largest mountains in Queensland, in size if not in height, will stand as a memorial to the wise policy of preserving features of the original Queensland, and will, at the same time, enable the many and not the few to holiday and learn from these national parks.

The 1961 amalgamation produced an area of 49,614 hectares. There have been further additions, and at least one subtraction, since then. The total area of Eungella National Park is now 59,865 hectares (Department of Environment and Science, *pers. comm.*). It is one of the great national parks of Queensland and Australia.

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THE EUNGELLA BIODIVERSITY STUDY: FILLING THE KNOWLEDGE GAP

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The rainforest of the Eungella massif has long been recognised as biologically unique: a centre of local endemism and an overlap zone with biota from both the tropical rainforests of north Queensland and sub-tropical elements from further south. We set out to study the rainforest biodiversity of Eungella National Park, and to collect data which would allow us to make predictions on how the fauna and flora of this area may respond to future climate change. Along an elevational gradient, a number of abiotic factors shift, including temperature, humidity and soil chemical properties. The Eungella Biodiversity Project was predicated on the use of an elevational gradient to understand how biological communities shift currently with climate, across elevation, in order to predict how this rainforest will respond to future climate change. We established permanent study plots along this elevational gradient and collected data on a range of groups including plants, moths, dragonflies, ants, snails and birds. Here, we give some background on the project and describe the botanic and environmental characteristics of the Eungella National Park elevational gradient.

Keywords: elevational gradient, microclimate, soils, vegetation

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INTRODUCTION

The rainforests of the Eungella region are truly special. This is the largest area of rainforest between the Wet Tropics to the north and the subtropical forests of the Queensland/NSW Border Ranges to the south. Despite Eungella's unique characteristics, long recognised by ecologists, botanists and geologists, there have been few (if any) large-scale inventories of the region's biodiversity. Most of the area's uniqueness has been inferred from opportunistic, taxonomically inspired collecting, often, ironically, as a waypoint as scientists based further south head for the biological riches of the Wet Tropics further north. Only one short article has discussed the special nature of the Eungella biota in general (Winter & McDonald, 1986).

Understanding the driving forces that shape biodiversity is imperative if we are to make informed management decisions, especially in a time of rapid ecological change. Much of the world's biodiversity is held in rainforests which cover only 7% of the world's land surface but contain half the world's biodiversity (Myers, 1984; Wilson, 1988). Many rainforests are experiencing rapid diversity loss, driven by anthropogenic forces including logging, conversion to agricultural land, and climate change (Mittermeier *et al.*, 1998; Sodhi *et al.*, 2010; Corlett, 2012). Over the course of the next century, climate change may well exceed the ability of many species to adapt *in situ* (Mantyka-Pringle *et al.*, 2012).

In the Australian context, multi-species, broad-leaved rainforests are scattered in moist pockets along the eastern seaboard from Tasmania to the tip of Cape York (Webb & Tracey, 1981; ABARES, 2016). These rainforest patches represent post-glacial remnants and, at the time of European invasion of Australia, covered about 43,500 km^2 (Stork *et al.*, 2008). About 70% (*ca.* 30,000 km^2) of this modest area remains after clearing for agriculture (Stork *et al.*, 2008; ABARES, 2016). Nevertheless, this small remaining area may well hold more than 50% of Australia's terrestrial biodiversity (Stork *et al.*, 2008).

During the 20th century, from 1914 onwards, increasing areas of remnant rainforests have been protected. Currently, nationally, an estimated 1.749 million hectares is located in national parks (48.5% of the total rainforest estate). A further 26% remains in private hands and 8% is leasehold. The remaining 17.5% is located in various 'minor' tenures (ABARES, 2016).

In Queensland, designation of 'rainforest' national parks began in 1908 when Witches' Falls National Park on Mount Tamborine was declared. This was followed in 1915 by declaration of the very much larger Lamington National Park (Jarrott, 1990). Most of the southern subtropical rainforests achieved World Heritage status in 1986 (extended in 1994) (Cavanaugh *et al.*, 2010). The northern 'wet tropical' rainforest was awarded similar status in 1988 (Valentine & Hill, 2008).

The reserve now known as Eungella National Park was established in a piecemeal fashon from 1936 onwards, being amalgamated into a single-named park in 1961 (Ogilvie, this volume). It currently comprises 59,865 hectares and includes extensive areas of rainforest. The name translates as 'Land of Cloud', and the area is the traditional home of the Wirri Aboriginal people (Birri Gubbi Aboriginal Corporation, 1996). The rainforests of Eungella are not included in either of the two rainforest-defined World Heritage Areas.

Eungella is one of the largest remaining areas of rainforest in Australia and is an intriguing mix of subtropical and tropical elements. The National Park is located on the edge of the Clarke Range, on a plateau including Mt Dalrymple and Mt William. Biogeographically, Eungella is bracketed by the Wet Tropics in the north and the Lamington/Border Ranges (and other) sub-tropical rainforests further south. There is, however, no connectivity among these patches, and extended areas of scleromorphic forests occur to both the north and the south. The flora and fauna of Eungella are mixtures of southern and northern elements, and often represents the southernmost or northernmost distribution limits for particular rainforest species.

Several features make Eungella a particularly important area of rainforest. The Eungella rainforests are surrounded by the semi-arid Brigalow, and now can be imagined as an island of rainforest surrounded by eucalypt woodlands, cattle grazing and sugar cane farming. This isolation may, over evolutionary time, have produced Eungella's several well known, endemic species of vertebrates, such as the Eungella honeyeater (*Bolemoreus hindwoodi*) and the Eungella torrent frog (*Taudactylus eungellensis*).

The forests of Eungella include a steep range from low to high elevations, adding to their vulnerability to climate change. Mountainous ecosystems are predicted to be particularly sensitive to climate change (Nogués-Bravo *et al.*, 2007). Climatically sensitive species are known to be shifting to higher elevations elsewhere (Chen *et al.*, 2011). Such compensatory shifts, however, are only possible if there is higher elevation habitat available. In addition, there are several other threats to the biodiversity of Eungella, including the effects of fragmentation, encroaching forest fires (Hines *et al.*, this issue) and introduced species, which may act synergistically to increase further the vulnerability and functioning of the Eungella ecosystems.

In 2004, a multidisciplinary biodiversity survey was carried out along an elevational gradient in the subtropical rainforests of Lamington National Park in South East Queensland. Insects and their relatives (the 'arthropods') and plants were the primary focus of this research. The IBISCA-Queensland (Investigating Biodiversity of Soil and Canopy Arthropods) Project involved a diverse group of about 40 arthropod specialists from 15 countries. Each participant collected data on their taxa of choice along the elevational gradient, which consisted of 20 sites spanning the full elevational distribution of rainforest in the region (Burwell, Nakamura & Kitching, 2011). Over the next five years, comparable surveys were carried out in the nearby Border Ranges National Park, and at Mt Lewis in far northern Queensland. Once these surveys were well advanced, it became apparent that the absence of a similar survey within the Eungella region – more or less midway between the extensive rainforests of South East Queensland and those of the Wet Tropics – represented a major gap in our knowledge of rainforests of Queensland. Funding from the Mackay Regional Council allowed this omission to be rectified and the subsequent incorporation of information from Eungella National Park into a larger data-set of elevational gradients across the eastern coast of Australia (Ashton *et al.*, 2016a; Ashton *et al.*, 2016b).

The Lamington, Mt Lewis and Eungella studies are all predicated on the idea that adjacent elevational bands can be used as a surrogate for changes in climate. Along an elevational gradient, a 200 m increase in elevation corresponds to an average drop of 1.2°C (Strong *et al.*, 2011). The underlying philosophy of the project has been that we can only predict the likely results of global warming on biodiversity by studying, in the here-and-now, how selected groups of animals and plants have responded to adjacent climates at increasing elevation. Further, only by establishing baseline data on current elevational distributions will we be able to detect future responses to change.

During the Eungella Biodiversity Study (hereafter EBS), 20 × 20 m plots were established, ranging from 200 m above sea level (asl). The approach of this study was similar to the original IBISCA project, gathering a range of experts on a variety of taxonomic groups (plants, insects, molluscs, birds) to concentrate their efforts on examining the same ecological questions using the same study sites, producing robust results in a relatively short time period. Data was collected in three main field trips (in October 2012, November 2013 and March 2014, respectively) led by Professor Roger Kitching of Griffith University. Local, regional and international scientists and volunteers collaborated to collect data on the distribution and community composition of a range of vertebrate, invertebrate and plant groups. Here, we describe the physical environment of the EBS elevational gradient and present the results of the vegetation surveys across the plots.

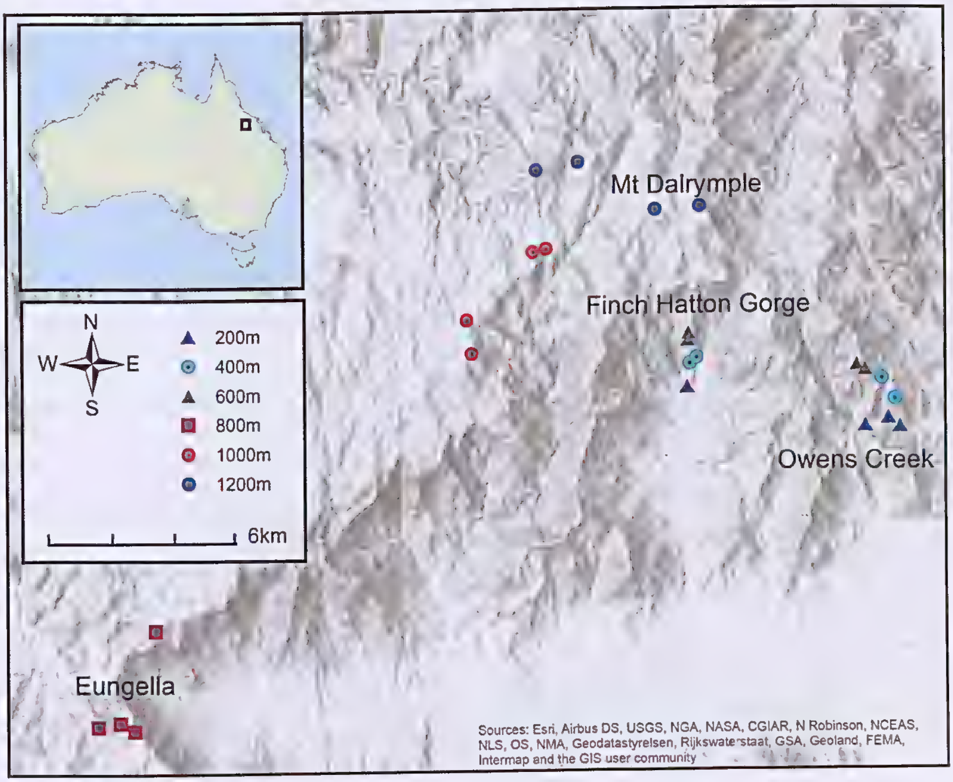
Materials and Methods

Study Sites

Eungella National Park (21°01′S 148°37′E) is located at the head of the Pioneer Valley, 80 km west of Mackay. Eungella forms part of the Clarke Range, and Mt Dalrymple is the highest peak at 1259 m asl. Eungella is an isolated island of rainforest, a remnant after climatic instability led to the retraction of rainforest extent over the last five million years (Weber *et al.*, 2014). It includes high-elevation, complex notophyll vine forests, and mesophyll forests at the lower elevations. Average annual rainfall is 2240 mm, which mostly falls during a short wet season from December to March, with major drainage through the Pioneer and Finch-Hatton Gorges. Eungella is characterised by well-drained, granite soils, kept moist by high orographic rainfall.

The elevational gradient was established between 200 m and 1200 m asl, running from Owens Creek up to 1200 m asl on Mt Dalrymple, Mt Henry and Mt Williams in Eungella National Park and the adjacent Pelion State Forest (Figure 1). We established four 20 × 20 m plots at each of six elevational bands (200, 400, 600, 800, 1000 and 1200 m asl) (Figure 1). Plots were placed at least 400 m apart and within ±50 m elevation of the designated bands. A full list of GPS coordinates is in Table 1.

FIGURE 1. Map of the 20 × 20 m sites established during the Eungella Biodiversity Project



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

Environmental Measurements

We deployed Thermochron™ temperature-recording iButtons across the elevational gradient at three plots per elevation; iButtons were placed in the understory (1.5 m) and in the upper canopy. A compound bow was used to shoot canopy lines, and iButtons were attached and pulled into the upper canopy; iButtons were deployed from November 2013 until July 2014, and temperature measurements were recorded every 3 hours.

TABLE 1. Latitude, longitude and elevation of the Eungella Biodiversity Study Plots

Plot	Latitude	Longitude	Elevation
200 – 1	–21.076628	148.687773	194
200 – 2	–21.074601	148.684886	181
200 – 3	–21.076414	148.679269	224
200 – 4	–21.067292	148.635147	244
400 – 1	–21.06185	148.635779	371
400 – 4	–21.060532	148.63755	386
400 – 6	–21.070207	148.686483	391
400 – 7	–21.065521	148.683299	426
600 – 1	–21.056426	148.635307	568
600 – 4	–21.054829	148.635533	606
600 – 6	–21.063384	148.679164	569
600 – 7	–21.06231	148.677169	621
800 – 1	–21.14472	148.498148	760
800 – 3	–21.142879	148.494652	755
800 – 6	–21.121806	148.503333	808
800 – 7	–21.143806	148.489083	816
1000 – 1	–21.058907	148.581798	1028
1000 – 2	–21.051234	148.580556	973
1000 – 3	–21.035762	148.597016	1001
1000 – 4	–21.03502	148.600345	972
1200 – 1	–21.016928	148.597991	1234
1200 – 2	–21.015093	148.608385	1164
1200 – 3	–21.026253	148.627429	1145
1200 – 4	–21.025577	148.63838	1225

We collected five 6 × 6 × 15 cm soil cores randomly from each of the four plots at each elevation, which were combined and homogenised. These were then analysed for soil chemical properties by Phosyn Analytical Pty Ltd, following protocols established by Rayment and Higginson (1992). Soil chemical properties included percent organic matter, cation exchange capacity, pH, salinity, and concentrations of elements including potassium, magnesium, calcium and sodium.

Vegetation

Within each quadrat, all living woody plant stems (excluding lianas) of greater than 5 cm diameter at breast height (dbh) were marked with individually numbered aluminium tags and their diameters measured. At two elevations, an additional one (400 m asl) or two (800 m asl) plots were also surveyed in order to better characterise these elevations. In total, over 1700 stems were tagged across the 20 survey plots. Species identification of the tagged trees was carried out by Bill McDonald, Dale Arvidsson and Irene Champion.

Analysis

We generated non-metric multidimensional scaling (NMDS) plots to illustrate the turnover in vegetation assemblages with elevation using the software package PRIMER. We used a square-root transformation on vegetation data to produce a Bray-Curtis dissimilarity matrix, and an NMDS ordination was created from this using 1000 permutations. Using the *a priori* elevational groupings of sites, we carried out PERMANOVA tests of similarity between pairs of elevational bands with 1000 permutations of the data.

RESULTS AND DISCUSSION

By sampling across an elevational gradient, the distribution and diversity of the rainforest flora and fauna of Eungella National Park were described. Together, we collected and identified 1720 tree stems, over 50,000+ moths belonging to over 1000 species, 8300 ants belonging to 120 species, 30 hours of bird observations and 240 hours of bird recordings. The overall moth fauna has already been described by Odell *et al.* (2016). Other papers in this volume cover snails, dragonflies, ants, birds and frogs, as well as a more detailed treatment of one superfamily of moths.

Temperature & Soil Properties

Understorey temperature dropped with increasing elevation by an average of 0.6°C per 100 m (Figure 2), and the canopy was on average 1.35°C hotter than the understorey, but there was variation across elevations (Figure 3). Some soil chemical properties shifted with elevation. Organic matter increased with increasing elevation, as did levels of aluminium and sodium

(Table 2). Cation exchange capacity, pH, calcium and the calcium:magnesium ratio all declined with increasing elevation. These patterns were generally the same as those found in the comparable survey we carried out at Lamington National Park (Strong *et al.*, 2011) except for cation (particularly sodium) exchange capacity which Strong *et al.* (2011) found to increase with elevation.

FIGURE 2. Frequency of average temperatures recorded at ground level across the elevational gradient. Temperatures were recorded between December 2013 and July 2014.

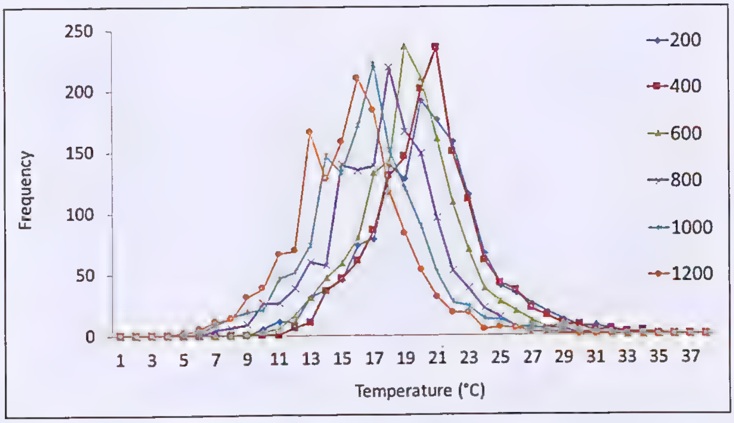


FIGURE 3. Frequency of mean temperatures measured in the understorey and canopy across elevational bands.

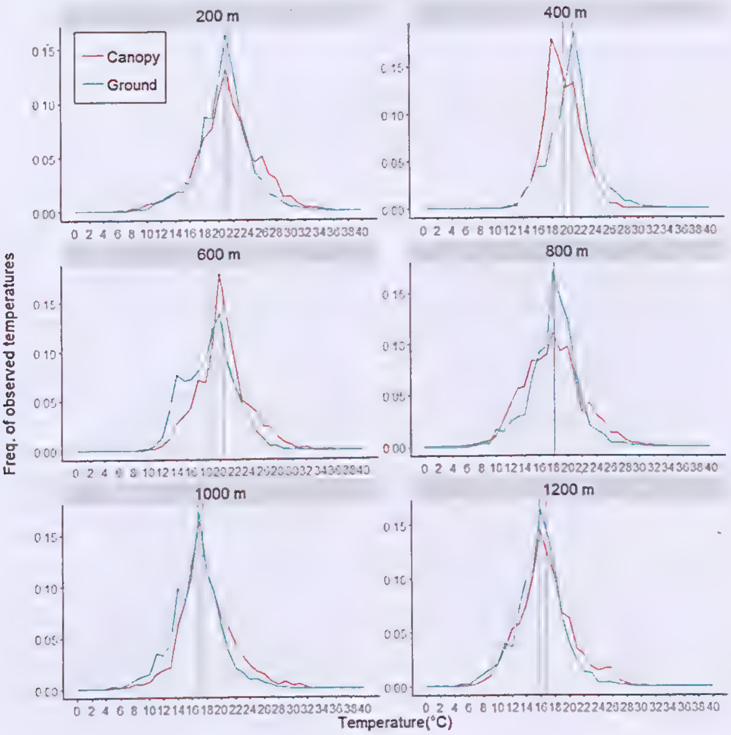


TABLE 2. Mean soil chemical and physical properties across elevations at Eungella

Soil physical property	200 m	400 m	600 m	800 m	1000 m	1200 m	Direction of change with increasing elevation
Organic matter (%)	9.925(1.35)	10.12(1.39)	11.95(2.57)	12.2(0.5)	16.62(1.48)	15.65(4.47)	Increasing
Cation exchange capacity (meq/100 g)	11.73(2.93)	8.46(2.89)	5.58(0.77)	11.4(1.85)	4.37(0.86)	3.65(0.43)	Decreasing
Ca:Mg ratio	3.5525(0.86)	3.15(0.86)	1.73(0.71)	3.33(0.14)	1.98(0.28)	1.16(0.42)	Decreasing
K base saturation (%)	3.45(1.29)	4.47(1.3)	6.7(0.87)	4.27(0.77)	7.05(0.69)	6.62(1.28)	NA
Mg base saturation (%)	20.95(3.07)	17.8(0.72)	24.65(3.95)	21.15(0.39)	23.9(1.26)	18.17(1.62)	NA
Ca base saturation (%)	66.52(10.57)	54.7(13.72)	40.92(13.34)	70.32(1.78)	47(6.22)	22(9.58)	Decreasing
Na base saturation (%)	1.3(0.27)	1.6(0.41)	1.97(0.41)	1.65(0.14)	2.47(0.23)	3.02(0.5)	Increasing
pH [1:5 $CaCl_2$]	5.6(0.21)	4.85(0.41)	4.12(0.4)	5.17(0.15)	4.25(0.13)	3.70.18)	Decreasing
pH [1:5 H_2O]	6.1(0.1)	5.65(0.35)	5.05(0.36)	5.85(0.12)	5.1(0.15)	4.55(0.24)	Decreasing
EC [1:5 H_2O] (dS/m)	0.12(0.01)	0.08(0.01)	0.09(0.01)	0.14(0.02)	0.09(0.01)	0.11(0.01)	NA
Al base saturation (%)	7.77(6.08)	21.42(11.65)	25.75(13.65)	2.57(0.61)	19.6(5.76)	50.15(10.77)	Increasing

Vegetation

The coarse results of the vegetation studies are summarised in Table 3. The 20 × 20 m plots established and replicated at each elevation recorded between 51 and 80 stems greater than 5ch dbh per plot. Average dbh ranged from 14.9 to 18.7 cm per plot. Finally, total tree basal area varied from 19,300 to 29,500 sq. cm per plot.

None of these statistics showed any obvious elevation-related trend. Table 3 lists the five commonest tree species encountered at each elevation in descending order of frequency of occurrence. A number of patterns are noteworthy. The palms, *Archontophoenix* spp. (Arecaceae), show partitioning by altitude. The widespread species *A. alexandrae* was a dominant at our sites up to 800 m asl. At 800 m and above, *A. cunninghamiana* also appeared as a dominant. This is a subtropical species recorded from southern NSW to Eungella, which is its northern distributional limit. Several 'tropical' species in our list of dominants reach their southern limits at Eungella. These include *Cryptocarya murrayi* (200 m asl), *C. corrugata* (1000 m asl) and *C. densiflora* (1200 m asl) (Lauraceae). In general, the *Cryptocarya* spp. we encountered were dominant only at particular elevations (or two adjacent elevations in the case of *C. glaucescens* (1000–1200 m asl)). The mid-elevation *Syzygium cryptophlebium* (600–800 m asl)(Myrtaceae) also reaches its southern limit at Eungella, as do *Acmena resa* (600 m asl)(Myrtaceae), *Rockinghamia angustifolia* (800 m asl)(Euphorbiaceae) and *Syzygium wesa* (1200 m)(Myrtaceae).

The total woody plant assemblages that we studied showed strong elevational turnover, with a clear separation in the assemblages into two broad categories: low (200–600 m asl) and high (800–1200 m asl) elevations (Figure 2). In addition, there were significant differences between the 600 m and 800 m plots, the 800 m and 1000 m plots, and the 1000 and 1200 m asl plots, whereas the 400 m and 600 m asl plots formed an overlapping vegetation assemblage (Figure 4 and Table 4). Three environmental variables were identified as significantly correlated with the turnover of vegetation assemblages in the DistLM analysis: Temperature (F = 4.21, P = 0.001), Organic matter (%) (F = 3.99, P = 0.006), and Sodium base saturation (%) (F = 3.4, P = 0.016); all DistLM results are listed in Table 5. Temperature and sodium base saturation declined with elevation, whereas levels of organic matter increased. Lower temperatures imply lower decomposition rates (and, accordingly, higher accumulation of organic matter). Sodium base saturation is considered a correlate of soil fertility (Laidlaw *et al.*, 2011), and such a change with elevation may reflect the history of erosion and leachng at the higher elevations.

The results of the pyraloid moth, ant, odonate, snail and bird surveys are presented in this volume. In general, results for all taxa show a clear turnover in community composition across the elevational gradient. Suites of indicator species – those which were common, easy to identify and sensitive to elevation (and by proxy, climate) – were identified. Odell *et al.* (2016) identified moth indicators which can be used to monitor future climate-driven distribution shifts. These may be combined with species from other taxonomic groups that were studied (ants, birds, snails) to form a 'predictor set' (*sensu* Kitching & Ashton 2013), a broad range of climatically sensitive species that have the potential to be used to monitor distribution shifts with future climate warming (Ashton *et al*., 2016b; Nakamura *et al*., 2016; Odell *et al*., 2016).

TABLE 3. Summary of the plot-based vegetation analyses

MEASURE	**ELEVATION BAND (metres) above mean sea level**					
	200.00	**400.00**	**600.00**	**800.00**	**1000.00**	**1200.00**
Average number of stems >5 cm per plot	63.5 ± 8.31	51.5 ± 7.64	71 ± 9.3	79.75 ± 7.36	64.75 ± 3.35	60.75 ± 8.28
Average dbh per plot (cm)	14.9 ± 1.14	17.68 ± 1.65	16.07 ± 0.82	14.99 ± 0.6	15.64 ± 0.6	18.67 ± 1.54
Total basal area per plot (sq.cm)	19,367.37 ± 3401.52	20,010.762 ± 569.61	29,204.49 ± 4549.45	21,385.42 ± 193.88	99,841.13 ± 8919.7	29,437 ± 2507.08
Species richness across elevation (all 5 plots)	49.00	39.00	46.00	32.00	43.00	25.00
Dominant 1	*Myristica globosa muelleri* (Warb.) W.J.deWilde – 32 stems	*Calophyllum australianum* F.Muell. ex Vesque – 25 stems	*Polyscias australiana* (F.Muell.) Philipson – 24 stems	*Archontophoenix alexandrae* – 138 stems	*Cryptocarya corrugata* C.T.White & W.D.Francis – 46 stems	*Niemeyera prunifera* (F.Muell.) F.Muell. – 52 stems
Dominant 2	*Archontophoenix alexandrae* (F.Muell.) H. Wendl & Drude – 30 stems	*Endiandra discolor* Benth. – 14 stems	*Acmena resa* (B.Hyland) Craven & Biffin – 23 stems	*Archontophoenix cunninghamiana* (H.Wendl.) H.Wendl & Drude – 30 stems	*Archontophoenix cunninghamiana* – 33 stems	*Cryptocarya glaucescens* – 35 stems
Dominant 3	*Cryptocarya murrayi* F.Muell. – 16 stems	*Myristica globosa muelleri* – 13 stems	*Endiandra discolor* – 22 stems	*Syzygium cryptophlebium* – 24 stems	*Cryptocarya glaucescens* R.Br – 18 stems	*Cryptocarya densiflora* Blume – 26 stems
Dominant 4	*Endiandra cowleyana* F.M.Bailey – 15 stems	*Pleioluma queenslandicana* (P.Royen) Swenson – 12 stems	*Syzygium cryptophlebium* (F.Muell.) Craven & Biffin – 21 stems	*Argyrodendron actinophyllum diversifolium* L.B.Sm. – 19 stems	*Cinnamomum olivieri* F.M.Bailey – 17 stems	*Syzygium wesa* B.Hyland – 17 stems
Dominant 5	*Cryptocarya hypospodia* F.Muell. – 15 stems	*Archontophoenix alexandrae* – 11 stems	*Cryptocarya vulgaris* B.Hyland – 20 stems	*Rockinghamia angustifolia* (Benth.) Airy Shaw – 18 stems	*Steganthera laxiflora laxiflora* (Benth.) Whiffin & Foreman – 12 stems	*Archontophoenix cunninghamiana* – 17 stems

FIGURE 4. NMDS of tree communities across elevation

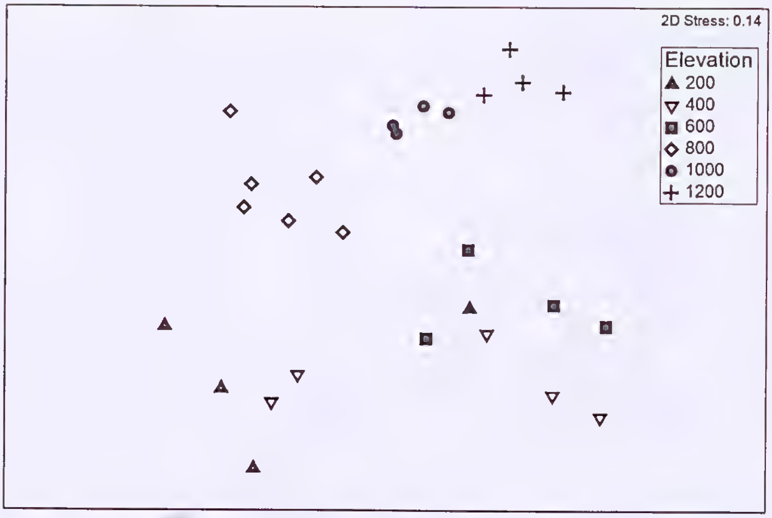


TABLE 4. PERMANOVA tests of plant community composition between adjacent pairs of elevational bands. Significant results are in bold.

Elevational groups (m asl)	t	P value (Monte Carlo)
200 and 400	1.10	0.29
400 and 600	1.06	0.33
600 and 800	**2.11**	0.006
800 and 1000	**2.19**	0.009
1000 and 1200	**2.41**	0.004

TABLE 5. Results of DistLM analysis testing the correlation of environmental variables and vegetation assemblages across elevation. Significant results are in bold.

Environmental variable	*F*	*P*
Temperature	4.21	**0.001**
Organic matter (%)	3.99	**0.006**
CEC (meg/100 g)	2.15	0.111
Ca:Mg ratio	2.28	0.115
K base saturation (%)	2.15	0.146
Mg base saturation (%)	0.52	0.761
Ca base saturation (%)	1.91	0.127
Na base saturation (%)	3.40	**0.016**
Al base saturation (%)	1.64	0.137
pH (1:5 $CaC1_2$)	2.16	0.117
pH (1:5 H_20)	2.39	0.095
EC (1:5 H_20)	0.79	0.533

The Eungella Biodiversity Study has generated large volumes of information, and several scientific papers from this work have now been published. These include the study of the elevational turnover of moths in Eungella (Odell *et al.*, 2016), cross-latitudinal studies of elevational patterns of moth (Ashton *et al.*, 2016b) and ant diversity (Burwell and Nakamura, 2016) and an assessment of the effectiveness of traditional bird surveys in comparison with automated acoustic recordings (Leach *et al.*, 2016). In addition, new species of snails identified as part of the Eungella Biodiversity Study are listed by Stanisic & Window, this volume. Other results are elsewhere in this volume.

Climate change is predicted to increase the frequency and severity of droughts and extreme weather events (Dai, 2013; Cai *et al.*, 2014). Eungella has been identified as a bioregion at risk, and it is important that the conservation value of this area is recognised and prioritised when developing management strategies. In November 2018, during a prolonged heatwave, Eungella suffered severe bush fires, which affected 110,000 hectares of forest (Hines *et al.*, this volume) which detroyed substantial areas of rainforest as well as surrounding brigalow (although not the research sites described here). Protected areas like Eungella National Park are not only important for conservation, but they also provide essential ecosystem services such as carbon storage, clean water and air, all of which will help mitigate the impacts of climate change. Conservation management strategies that include planning for the future of Eungella National Park under climate change are needed for this region. The inclusion of Eungella National Park as a world heritage area is being discussed by government, and would help meet conservation goals, as well as enhance the profile and local economy of nature-based tourism. Including Traditional Owners, local communities and local conservation groups in planning for the future of Eungella is essential.

Extinction has already occurred in Eungella, with the last sighting of the northern gastric brooding frog (*Rheobatrachus vitellinus*) occurring in 1985. If the rainforest at Eungella is lost, a large portion of the biodiversity of Queensland is also lost. Understanding the multiple threats to this area, including climate change and habitat loss, is essential for the conservation of Eungella. The Eungella Biodiversity Study establishes benchmark datasets on the current elevational distributions of plants and animals, all of which are publicly available, and can be used to monitor the impacts of climate change in the future.

A full list of species and their abundances in each of the plots is available online at: https://osf.io/vsfr9/

ACKNOWLEDGEMENTS

The results of the EBS represent thousands of hours of fieldwork, laboratory sorting and identification by collaborators from Griffith University, the Queensland Herbarium, the Mackay Regional Botanic Garden, the Queensland Museum and the Chinese Academy of Sciences. This project was made possible by the efforts of many volunteers from Eungella and Mackay, including community groups such as the Mackay Bushwalking Club, Birdlife Mackay and Reef Catchments.

The Eungella Biodiversity Project was generously funded by the Mackay Regional Council. We thank, in particular, the Mayor, Councillor Commerford, their Chief Executive Officer Dan McKinlay, and other officers of the Council who gave us their support.

The Survey also formed part of the work schedule of the Queensland State Government/Chinese Academy of Science Joint Biotechnology Project (part of the 'Smart State' initiative) which funded much of the preliminary work before the Survey actually took place. We are most grateful for this support.

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LAND SNAILS OF THE EUNGELLA PLATEAU AND ENVIRONS, CLARKE RANGE, MID-EASTERN QUEENSLAND

STANISIC, J.[1] & WINDOW, E.[2]

This study documents the land snails recovered on the Eungella Biodiversity Survey. Thirty-three species belonging to 10 families are documented, representing the first attempt at analysing the altitudinal stratification of the Eungella land snail fauna. Three species were newly recorded and subsequently described from the survey, these being *Eungellaropa crediton* Holcroft 2018, *Burwellia staceythomsonae* Holcroft & Stanisic 2018, and *Pereduropa burwelli* Holcroft & Stanisic 2018. *Fastosarion comerfordae* Stanisic 2018 was also described from the survey material, having previously been confused with the Mt Dryander *Fastosarion superba* (Cox, 1871). Species are discussed in relation to their current taxonomy, their local and more widespread distributions, and their habitat and microhabitat preferences. Shortcomings of the land snail survey are also briefly discussed. A biogeographic overview of the Eungella rainforest land snails is presented.

Keywords: elevational gradient, land snails, taxonomy, distributions

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INTRODUCTION

The Eungella Biodiversity Survey (EBS) of 2014–2015 (Ashton *et al.*, this volume) was the first concerted effort at surveying and documenting the land snails of the Eungella plateau and environs. Previous land snail collecting in the area by the Queensland Museum (QM) comprised only short-term visits that formed part of more wide-ranging expeditions. The expansive Australian Museum, Sydney (AMS)/QM rainforest biodiversity surveys of the mid-1970s included land snails as a target group. Sites at Finch Hatton and Crediton were visited, but the results for land snails were never documented. The Eungella region of the Clarke Range encompasses some of the highest peaks (Mt Henry, Mt William, Mt Dalrymple) encountered in the Clarke-Connors bioprovince of the Central Mackay Coast (CMC) bioregion. Rainforest on the Eungella plateau (altitude 800–1200 metres) consists of subtropical notophyll vine forest almost grading to more tropical mesophyll vine forest in some areas. At lower altitudes (200–600 metres), notophyll vine forest persists in sheltered gorges (Finch Hatton) and along drainage lines. Riparian habitats with uninterrupted connections with montane rainforest are important secondary habitats for land snails and provide corridors for dispersal. Hence, given the predilection of land snails for humid wet forests along the length of the continent's eastern seaboard, the Eungella region appears to offer a number of prime habitats for a robust community of land snails.

METHODS

Site locations and site descriptions are presented in Ashton *et al.* (this volume). Survey effort per site comprised one person-hour searching favoured snail microhabitat including both terrestrial and arboreal niches. Land snails were hand-collected as live specimens, dead shells, and from leaf litter sorting by microscope. The latter is an important source of micro-snails (Charopidae, Punctidae) whose shells are usually less than 4 mm in diameter. These micro-snails are usually collected as dead shells that nonetheless can be identified as species and, where necessary, formally described. Leaf litter collection involves taking the decaying leaves and top 1–2 cm of soil from places where dead shells accumulate.

Land snail collection during the day (as was the case with the EBS), and even at night, can be hit and miss because they are nocturnal creatures that are very sensitive to ambient conditions. Collecting after rain events when snails are most active and sheltering in the top layer of forest debris gives the best results. The EBS snail survey was conducted in ideal rainy conditions. But even then, the patchy distribution of species in the litter zone does not guarantee finding a species at a site. Furthermore, a number of species that are catalogued in the QM collections as occurring at Eungella are absent from the final list. Personal experience has shown that follow-up collecting should result in more species being added to the inventory. A presence is a positive result, but an absence should not necessarily be considered an absolute absence, both from a site and the entire EBS.

In some sites leaf litter collection was not possible. Areas had been scoured by heavy rain, with little or no litter to be collected. This was particularly noticeable in the Diggings Road and Eungella Dam Road where palm fronds were all that formed the layers of forest debris. It is with these caveats that results of the EBS need to be scrutinised and analysed.

RESULTS

General identification and classification followed Stanisic *et al.* (2010). Additional identification is provided in Holcroft (2018b), Holcroft & Stanisic (2018) and Stanisic (2018). Thirty-three species of land snails belonging to ten families were catalogued from the 24 sites visited (Table 1). To put these numbers into perspective, the Queensland Museum collections hold more than 140 species from the entire CMC bioregion. The EBS collections form a small and circumscribed subset concentrated on the Eungella region. Twenty-six of the species collected on the EBS were already described and a further seven recognised as putative new species yet to be formally described. Four of the described species (*Eungellaropa crediton*, *Burwellia staceythomsonae*, *Pereduropa burwelli*, *Fastosarion comerfordae*) were found on, and subsequently described (Holcroft, 2018b; Holcroft & Stanisic, 2018; Stanisic, 2018) from, material collected on the EBS. For this report the species included in the undescribed cohort are identified by a descriptor comprising family name with an alpha-numeric suffix, e.g. Helicinidae MQ 2. This is a system used throughout the QM and AMS land snail collections to denote putative species.

SYSTEMATIC ANALYSIS

The land snails of the EBS fall into two morphologically distinct groups: the small minority are operculates which have an operculum (to seal the shell opening), separate sexes, an open pallial cavity and absorb oxygen directly from the air. The much more dominant pulmonates, which lack an operculum, are hermaphrodites and breathe by means of a lung. Operculates (neritopsinids and caenogastropods) are almost exclusively confined to wetter rainforests and vine thickets. In contrast, pulmonates, having a closed lung that can also act as a 'water bag', have the ability to inhabit a much more diverse array of environments ranging from very wet rainforest to arid desert.

The operculates are represented by five species in the EBS. These belong to the two families historically associated with MEQ.

Superorder Neritopsina, Family Helicinidae

The arboreal Mt Dryander Droplet Snail, *Pleuropoma queenslandica* Stanisic, 2010, was the most commonly encountered operculate land snail. This species lives on the leaves of trees, especially palms, and occurred from the lowlands in riparian habitat (200 m, Sites 1 & 2) to the 1200 m Site 2 on Mt Henry. This species also occurs in the Conway Range and at Mt Dryander of the Whitsunday bioprovince and displays the typical locally widespread distribution pattern associated with arboreal species that are open to wind-blown dispersal. A second, putative new species (Helicinidae MQ 2), endemic to the higher reaches of the Clarke Range, was recorded from the Dalrymple Road (1000 m, Site 1).

Superorder Caenogastropoda, Family Pupinidae

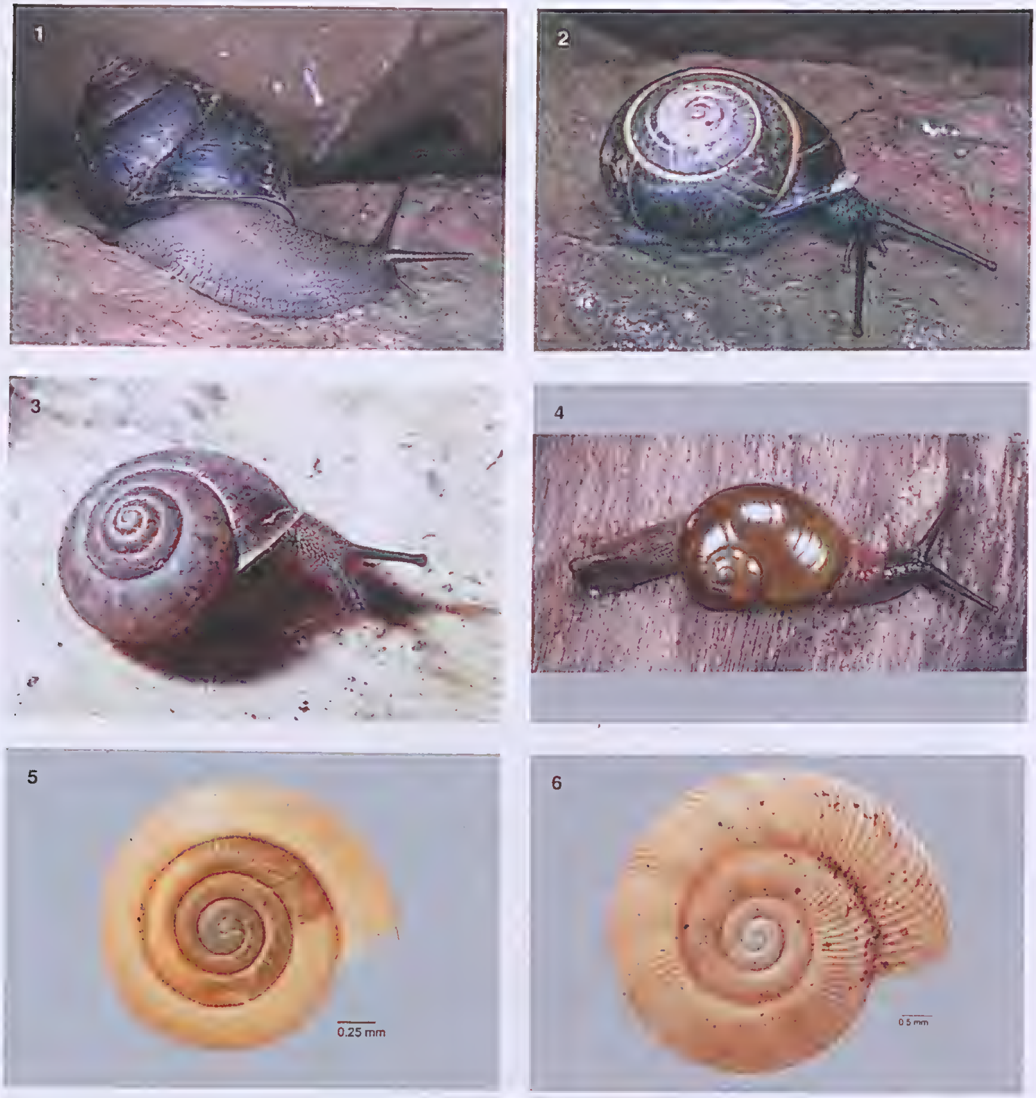
The ground-dwelling Golden Chrysalis Snail, *Signepupina meridionalis* (Pfeiffer, 1864), was the second most commonly encountered operculate land snail. Pupinids are somewhat specialised in their range of microhabitat preferences in that they can be found inside very wet, rotten logs. Land snails in general like moist but not overly moist microhabitats. Too much moisture will cause the snail to hyper-secrete mucus, resulting in considerable stress and death. A second species, the Glossy Eungella Chrysalis Snail, *Signepupina masoni* Stanisic, 2010, was recorded at the 200 m, 400 m and 600 m elevations. Records of the QM indicate that this species is also common in the Crediton and Eungella areas at elevations of 800–1000 m. A third putative species (Pupinidae MQ 6) was represented by a single record from a site along Owens Creek (200 m, Site 1) This species is more common in the lowland rainforest around Sarina.

The pulmonates are represented by 28 species belonging to 10 families in two orders.

TABLE 1. List of snails encountered in the Eungella Biodiversity Survey ordered by elevation and study site

EBS snail data 1914–1915	200 m				400 m				600 m				800 m				1000 m				1200 m			
	1	2	3	4	1	4	6	7	1	4	6	7	2	4	6	7	1	2	3	4	1	2	3	4
Pleuropoma queenslandica	x	x					x	x										x				x		
Helicinid MQ 2																	x							
Signepupina macgillivrayi		x						x			x													
Signepupina masoni				x				x																
Pupindae MQ 6	x																							
Atopos australis					x		x	x						x	x									
Pupisoma porti														x										
Coelocion australis							x																	
Briansmithia clarkensis	x							x							x	x		x						
Pandofella whitei		x																						
Punctidae MQ 2					x			x							x	x				x		x		
Biomphalopa recava																				x		x		
Burwellia staceythomsonae																							x	
Charopid MQ 28												x												
Charopid MQ 13																								x
Eungellaropa crediton					x								x											x
Isolderopa deliqua																						x		
Isolderopa iangallowayi	x				x															x				
Isolderopa minuta	x			x										x	x			x	x	x	x	x	x	
Pereduropa burwelli				x						x			x				x	x						
Setomedea janae																						x		
Stanisicaropa chambersae				x						x			x			x	x	x						
Triboniophorus graeffei																	x							
Coneuplecta calculosa		x	x																					
Eddiella proserpiniana																		x						
Eddiella nana			x				x				x						x	x		x				
Eungarion mcdonaldi																x	x					x		
Fastosarion comerfordae								x	x	x	x	x		x	x		x	x	x		x	x	x	x
Helicarionid MQ 13	x	x	x		x	x	x	x			x	x			x									
Helicarionid MQ 16																	x							
Trachygenia praecursoris							x				x	x			x	x								
Sphaerospira informis	x	x	x		x			x			x			x	x	x	x		x					
Sphaerospira oconnellensis		x					x							x										

EUNGELLA LAND SNAILS. 1, *Sphaerospira informis* (Mousson, 1869); 2, *Sphaerospira oconnellensis* (Cox, 1871); 3, *Trachygenia praecursoris* (Hedley, 1912); 4, *Fastosarion comerfordae* Stanisic, 2018; 5, *Pereduropa delicata* Stanisic, 2010; 6, *Stanisicaropa chambersae* Stanisic, 2010.



Order Systellomatophora, Family Rathouisiidae
The Australian Prism Slug, *Atopos australis* (Heynemann, 1876), is one of only a handful of Australian native slugs. Inhabiting wet rainforests from the Torres Strait islands to Wauchope in mid-eastern New South Wales, *A. australis* is the only Australian representative of the family. Additional species are found in Papua New Guinea and Southeast Asia. The slug was recorded from 400 m and 800 m sites and is probably present at the 600 m sites. The species appears to prefer mid-altitude habitats throughout its extensive range.

Order Eupulmonata
This order included the largest grouping of EBS snails, comprising 27 species belonging to ten families. Three

families (Charopidae, Helicarionidae, Camaenidae) dominate the east coast land snail fauna, and all are well represented in the EBS.

Family Pupillidae. A single species of this family, the Tall Toothless Pupasnail, *Pupisoma porti* (Brazier, 1876), was recorded as a dead shell at the 800 m elevation off Eungella Dam Road (Site 4). The species is uncommon in wetter rainforests, preferring drier rainforest and vine thickets. *P. porti* lives on the branches of shrubs and under bark of standing trees.

Family Megaspiridae. The Australian Megaspire Snail, *Coelocion australis* (Forbes, 1851), was recorded at only one site along Owens Creek (400 m, Site 6), although QM records show the species to be common at other sites in the Eungella section of the Clarke Range. The species prefers drier araucarian rainforests and lives among rocky rubble. This microhabitat was scarcely encountered during the EBS and probably explains its absence in most sites.

Family Rhytididae. This family of carnivorous snails comprises both large and very small species. A single large species, the Clarke Range Carnivorous Snail, *Briansmithia clarkensis* Stanisic, 2010, was recorded from five sites at elevations ranging from 200–1000 m. Carnivorous snails are typically low in numbers in snail communities when compared with other species.

Family Caryodidae. Previously only known from the upland rainforests of the Clarke Range (Eungella, Mt Dalrymple, Mt Macartney), the Slug-like Panda Snail, *Pandofella whitei* (Hedley, 1912), was recorded from a 200 m site (Site 2) along Owens Creek. Being unable to retract into its reduced half-shell, the species is extremely prone to desiccation and typically prefers very wet rainforest habitats. The presence of *P. whitei* in lowland riparian rainforest was unexpected.

Family Punctidae. A single putative species, tentatively identified as the Miniscule Pinhead Snail, *Iotula microcosmos* (Cox, 1868), was recorded across several elevations ranging from 400–1200 m. This is a widespread species occurring in wet rainforests and vine thickets from south-eastern New South Wales to mid-eastern Queensland. It is one of Australia's smallest land snails, with a shell diameter of 1.2 mm.

Family Charopidae. The Charopidae is the dominant family of east coast land snails, with an estimated 750 species but comprising many that still have to be described. The family also dominates the EBS fauna with eleven species recorded. Until recently the charopid fauna of MEQ consisted of 12 species. Following the studies of Holcroft (2018a, 2018b) and Holcroft & Stanisic (2018), this number has increased to 37 with many putative species yet to be described and possibly many more to be discovered. The majority of these species are endemic to the CMC bioregion, specifically the Clarke Range. QM records show that ten of the species collected in the EBS are Clarke Range endemics. Several of these are exclusively endemic to the higher elevations of the Clarke Range. These comprise the Caramel-flamed Pinwheel Snail, *Biomphalopa recava* (Hedley, 1912), Ranger Stacey's Pinwheel Snail, *Burwellia staceythomsonae* Holcroft & Stanisic, 2018, and the putative Charopid MQ 13. The high local endemicity of the charopid fauna is typical of large rainforest tracts in eastern Australia. These snails are usually recovered as dead shells through leaf litter sorting, and their live counterparts are very difficult to find because of their small size and associated ability to fit into the narrowest of crevices.

Family Athoracophoridae. The Red-triangle Slug, *Triboniophorus graeffei* Humbert, 1863, was recorded in the EBS from a single specimen. The species is widely distributed in eastern Australia, ranging from south-eastern New South Wales to north of the Wet Tropics, north-eastern Queensland. Records show that the species is uncommon in MEQ. The slug displays a wide range of colour forms throughout its range, varying from golden-yellow to orange to red. *T. graeffei* is currently under revision and early indications are that the taxon is an umbrella for a number of undescribed cryptic species of which the MEQ may be one.

Family Euconulidae. The widespread Tropical Beehive Snail, *Coneuplecta calculosa* (Gould, 1852), was collected from several sites during the EBS. *C. calculosa* is an arboreal species widely distributed in subtropical and tropical rainforests in eastern and northern Australia. The species also has a wide presence on land masses in the south-west Pacific region. Wind dispersal is probably responsible for the extensive range of the species.

Family Helicarionidae. This family includes both glass snails with a full shell and semi-slugs with a reduced ear-shaped shell. Semi-slugs of the family Helicarionidae have a reduced ear-shaped shell into which the snail can no longer withdraw to escape a snail's two worst enemies: predators and desiccation. They are therefore mainly active in the most humid parts of the day (early morning and early evening) or during and after rain. The moist Eungella rainforests are inhabited by several semi-slug species, but none more spectacular than the large, black Comerford's Semi-slug (*Fastosarion comerfordae* Stanisic, 2018) which can usually be found inside rolled-up, fallen palm fronds on the forest floor. This species has close relatives living in the Conway Range, Mt Dryander and in the northern Wet Tropics, and is one of the few MEQ land snails that still show past connections with the rainforests of the north. In contrast, the somewhat smaller, endemic and restricted McDonald's Semi-slug (*Eungarion mcdonaldi* Stanisic, 1993) can be found inhabiting the leaves and branches of low rainforest shrubs in the higher-rainfall areas of Eungella. This species has a shell which is almost plate-like and very membranous. Two unnamed species of semi-slug were also recorded (Helicarionid MQ 13, Helicarionid MQ 16) during the survey. Helicarionid MQ 13 was found at many sites at elevations ranging from 200–800 m. A single specimen of Helicarionid MQ 16 was located at the 1000 m elevation, Site 1. Two species of glass snail were also recorded. This group of helicarionids is currently under revision and identifications are tentative and broad, pending the outcome of that study. *Eddiella proserpiniana* Stanisic, 2010, has a very wide distribution in the MEQ region that includes the Eungella plateau. The much smaller *Eddiella nana* Stanisic, 2010 has a more restricted distribution encompassing the Eungella plateau. Records of the QM have this species also occurring on the off-shore islands and in the drier scrubs west of Eungella, suggesting that more than one species is involved.

Family Camaenidae. Mid-eastern Queensland has a great variety of large snails belonging to the family Camaenidae, and several of these occur in the Eungella area. Most notable is the very large Giant Mid-eastern Snail, *Sphaerospira informis* (Mousson, 1869), which lives under logs and rocks. This species has a distribution encompassing the Clarke Range but also extending to the Proserpine-Sarina lowlands. An outlier population has been recorded from Connors Hump, east of St Lawrence. A sister species, the O'Connell River Dark Snail, *Sphaerospira oconnellensis* (Cox, 1871), co-occurs with the former, but is micro-allopatric. Rather than living under logs and rocks, this species is usually found under bark of standing trees and fallen logs. This species has also been recorded farther south in the Connors Range. Another camaenid, the Eungella Bristle Snail, *Trachygenia praecursoris* (Hedley, 1912), which is distinguished by having tiny hairs on the shell surface, is also a common inhabitant of these rainforests. The species occurs in the higher reaches of the Clarke Range and Connors Range from Mt Macartney to the Blue Mountains, south-west of Sarina.

DISCUSSION

The land snail fauna of MEQ is diverse in its make-up and derivation. This pattern is strongly reflected in the results of the EBS. The Eungella region and its rainforests have had relatively few mentions in past discussions of east coast rainforest biogeography (Webb & Tracey, 1981; Adam, 1992) which have focussed chiefly on the Wet Tropics of North Queensland or on the central eastern rainforests of southern Queensland and northern New South Wales. The lack of significant numbers of vertebrate and plant endemics in the region seems to have been the major driver of this lack hiatus. However, the scarcity of detailed studies of the invertebrates of the CMC region, as well as in areas to the north and south, is the primary reason for their absence in these discussions. Yet these animals, especially those with low vagility such as land snails, may potentially have significant input into future biogeographic analyses involving CMC mesic communities. The recent study of Rix & Harvey (2012) on assassin spiders is the exception and a case in point.

Land snails present an ideal opportunity to contribute to the biogeographic dialogue. Although the study of land snails in the CMC is still in its infancy, there is a mounting volume of morphological data and preliminary molecular data which, when combined with robust distribution data, is fuel for informed speculation and hypotheses (Stanisic, 1990; Stanisic, 1993; Stanisic *et al.*, 2010; Hugall & Stanisic, 2011; Holcroft, 2018a; Holcroft, 2018b; Holcroft & Stanisic, 2018; Stanisic, 2018). The absence of comprehensive molecular data on land snails, similar to that provided by Rix & Harvey (2012) for assassin spiders, should not be an impediment to progressing these discussions.

The EBS land snail results provide a platform for initiating these conversations. The following discussion is presented in the wider context of the entire CMC bioregion.

Biogeographic analysis

The MEQ rainforests are isolated by two major dry corridors: the large and highly influential Burdekin Gap in the north and the somewhat smaller St Lawrence Gap in the south (Bryant & Krosch, 2016). Vicariance, driven by the onset of climate-induced continental aridity in the early Miocene, gradually isolated the MEQ rainforest communities and their land snails from those in the north and south as these corridors became established. Joseph *et al.* (1993) suggested that connections with the south would have been maintained for longer than those with the north through an archipelago of drier vine thickets and that their separation would have been relatively more recent. The associated drying during the many glacial periods of the Plio-Pleistocene would have had significant consequences for the MEQ mesic communities, especially moisture-sensitive taxa such as land snails. This led Galloway & Kemp (1981) to conclude that these changes would have placed considerable stress particularly on montane environments, leading to many episodes of extinction, and that modern communities in these situations are recent phenomena consisting of biota that have survived in isolated refuges. Winter (1988) suggested that MEQ rainforests contracted to such small areas during this period that rainforest specialist mammals would not have survived. However, land snails do not need large-acreage landscapes to exist and persist.

Throughout the period of MEQ mesic habitat reduction (but not complete elimination) during the Quaternary, land snails would have been able to survive in arrow-head gullies, riparian habitats and scattered lithorefugia where remnant rainforest would presumably have persisted, albeit in very small patches. The MEQ land snails, particularly those of the uplands and environs, are modern-day survivors of these past episodes of climatically induced environmental sifting.

The following discussion is limited to the pulmonates, with brief mention of the operculate families.

Biogeographically, the pulmonate land snails of the EBS fall into two main groups. These are the southern or Gondwanan families (Athoracophoridae, Charopidae, Rhytididae, Caryodidae, Megaspiridae) and the northern post-Miocene immigrant families (Camaenidae, Helicarionidae, Rathouisiidae). Families that are part of wider world distributions include the Pupillidae and Punctidae. While the lack of robust phylogenies hinders rigorous biogeographic analyses, several generalisations about the former two groups are possible.

Both the Caryodidae and the Megaspiridae reach their northern limit in the CMC bioregion and do not appear to have been able to colonise north of the Burdekin Gap. The nearest relatives of the caryodid, *Pandofella whitei*, are in south-eastern Queensland, south of Gympie in the form of the Giant Panda Snails, *Hedleyella falconeri* (Gray, 1834) and *H. maconelli* (Reeve, 1854). Both are wet rainforest species, and the evolution of drier forests in the intervening areas between Gympie and the CMC leads to the conclusion that there have been extinctions of related forms in these areas. The megaspirids, on the other hand, have been able to radiate in the drier araucarian forests of southern and central Queensland. Apart from *Coelocion australis* in the CMC, congeners occur in both the Bobby Range (*C. circumumbilicata* Stanisic, 2010) and Lockyer Valley (*C. craigeddiei* Stanisic, 2010) in the southern Queensland brigalow belt (Stanisic *et al*., 2010). The Athoracophoridae and Rhytididae span both the St Lawrence and Burdekin Gaps, with the Rhytididae ranging from Tasmania (*Tasmaphena* spp.) through to the Torres Strait (*Torresiropa* spp.). The Athoracophoridae range from the south coast of New South Wales to north of the Daintree, north-eastern Queensland. Both groups appear to have established their broad presence before the advent of the dry corridors along the eastern seaboard and have managed to maintain that foothold through the subsequent period of climatic attrition. Their survival in the Eungella rainforests is a measure of their resilience.

Similarly, the highly speciose Charopidae has numerous species ranging from Tasmania through to the Wet Tropics in north-eastern Queensland. Historically considered a temperate group, this family has been shown to be a significant faunal unit in the subtropics and tropics (Stanisic, 1990; Stanisic *et al*., 2010). Of the EBS taxa, *Setomedea janae* has congeners in both southern [*S. seticostata* (Hedley, 1924)] and north-eastern Queensland (*S. monteithi* Stanisic, 1990): *Biomphalopa recava* has links with the Wet Tropics [*B. concinna* (Hedley, 1924)] but no relatives in the south. These are ancient distributions that once again show the survival ability of these tiny species in CMC refugia in the wake of mesic forest contraction since the early Miocene. However, there is also evidence of CMC extinctions in this family. The arboreal *Hedleyoconcha* Pilsbry 1893 has congeners in the south [*H. delta* (Pfeiffer, 1857)] and in the north (*H. ailaketoae* Stanisic, 1990) but none in the central Queensland rainforests (Stanisic, 1990). Arboreal existence is more prone to the vagaries of climatic change, and the absence of this tree-dwelling genus in the CMC bioregion has analogues in the Camaenidae. This family has tree snails in both southern and northern Queensland rainforests but none in the CMC coast. The Charopidae also show a high degree of endemism in the Eungella rainforests, exemplified by the relictual *Burwellia staceythomsonae* (see Holcroft & Stanisic, 2018) attesting to the significance of the tiny Plio-Pleistocene refugia of the higher reaches of the Eungella plateau.

The Rathouisiidae, a family of northern origin, is represented in the EBS by a single species, *Atopos australis*. Considered a single species that ranges from Cape York to central New South Wales, *A. australis* shows a similar distribution range to both the operculate families, Helicinidae and Pupinidae. Together they display a wave of colonisation that preceded the creation of the St Lawrence and Burdekin Gaps. *A. australis* is an obligate wet rainforest dweller, while the operculate families have been able to radiate into drier rainforest scrub throughout their vast ranges.

Both the Helicarionidae and Camaenidae have a dominant presence in eastern Australian rainforests. The two families are present down much of the eastern seaboard from Cape York to Tasmania (Helicarionidae) and southern Victoria (Camaenidae). Both have managed to disperse prior to the formation of the many dry corridors (Byrant & Krosch, 2016) that have affected other families of land snails. The semi-slugs of the Helicarionidae have dispersed as far south as Tasmania, whereas the helicarionid glass snails have not managed to cross the Southern Transition Zone. This is counter-intuitive since the glass snails as a group show a much wider tolerance to environmental conditions than do the semi-slugs. This is shown in the EBS by the local endemism of *Fastosarion comerfordae*, *Eungarion macdonaldi* and Helicarionid MQ 16 in contrast to *Eddiella nana* and *Eddiella proserpiniana*. Three genera of large MEQ camaenid land snails belonging to the hadroid lineage (*Bentosites* spp., *Marilynessa* spp., *Sphaerospira* spp.) occur in the CMC bioregion. *Sphaerospira informis* and *S. oconnellensis* are the only two species found during the EBS, and both have wider distributions within the CMC and along the southern Connors Range but not south of the St Lawrence Gap dry corridor. Congeneric relatives occur in the rainforest of the Byfield area [*S. mortenseni* (Iredale, 1929)], the drier vine thickets and rainforest refugia of the Rockhampton-Gympie region [*S. rockhamptonensis* (Cox, 1873), *S. blomfieldi* (Cox, 1864), *S. bencarlessi* Stanisic, 2010, *S. sidneyi* (Iredale, 1933)] and in the Border Ranges [*S. fraseri* (Griffith & Pidgeon, 1833)]. This genus appears to have been isolated south of the Burdekin Gap, with two species isolated in the CMC by the two dry corridors to the north and south. Interestingly, no camaenid tree snails occur in the MERQ. This group of Australian land snails, once thought to form a singular taxonomic group (Papuinidae), was shown by Hugall & Stanisic, 2011) to comprise independently derived species from local terrestrial forms. Their absence in MEQ is considered to be a reflection of the severe climatic attrition of mesic communities, especially arboreal species.

CONCLUDING REMARKS

The above discussion, while somewhat tentative, shows that land snails can be useful in outlining the chronological sequence of events that have moulded east coast mesic communities. Their responsiveness to both local and broad landscape changes caused by climatic fluctuation suggests that they could be, given further study, the exemplar invertebrate group for interpreting east coast biogeography.

ACKNOWLEDGEMENTS

We thank Lorelle Holcroft for assistance with species cataloguing.

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DRAGONFLIES AND DAMSELFLIES (ODONATA) OF THE EUNGELLA REGION, CENTRAL COASTAL QUEENSLAND, AUSTRALIA

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We collate records of species of dragonflies and damselflies (Odonata) from the broader Eungella region within the Clarke Range, central coastal Queensland, Australia, comprising the Eungella plateau, the upper Pioneer Valley as far east as Gargett, and the area around Eungella Dam on the western side of the Clarke Range. Records are based on specimens collected on Griffith University and Queensland Museum surveys of the region in 2013 and 2014, specimen records in museum collections, and observational records sourced using the *Atlas of Living Australia* and accompanied by identifiable photographs. A total of 58 species are recorded from the Eungella region: 37 dragonflies and 21 damselflies, representing 12 families. Four species appear to be endemic to the Clarke Range. Another six are southern species that occur as far north as Eungella and the broader Clarke Range but do not cross the Burdekin-Lynd Barrier. Two species are essentially confined to northern Queensland and occur south of the Burdekin-Lynd Barrier but only as far south as the Eungella region. The majority of the region's species are widespread, occurring from northern to southern Queensland and often far beyond.

Keywords: dragonflies, damselflies, Odonata, Eungella

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INTRODUCTION

Within the Central Queensland Coast (CQC), the region extending from just north of the town of Proserpine to south of Sarina, the Clarke Range contains the greatest extent of upland rainforest. The Eungella region is located approximately 60 to 70 km west of the city of Mackay, in the southern part of the Clarke Range. The upland rainforests of the Clarke Range are a centre of endemism for both invertebrates (Morgan, 1988; Monteith, 1997; Colloff, 2010; Holcroft, 2018) and vertebrates (Longmore & Bowles, 1983; Sadlier *et al*., 2005; Slatyer *et al*., 2007), although to a much lesser degree than the rainforests of the Wet Tropics bioregion to the north. The significance of the odonate fauna of Eungella was highlighted by Watson & Theischinger (1984), and over the next decade four species were described from the Eungella region, *Episynlestes intermedius* (Theischinger & Watson, 1985), *Austroargiolestes elke* (Theischinger & O'Farrell, 1986), and *Austroaeschna christine* and *Austroaeschna eungella* (Theischinger, 1993), all of which appear to be restricted to the Clarke Range. The Eungella region is also the northernmost extent of the range of a number of dragonfly and damselfly species (Watson & Theischinger, 1984). Despite its significance, there has been no overview of the region's odonate fauna.

In 2013 and 2014, Griffith University and the Queensland Museum conducted the Eungella Biodiversity Survey, systematic surveys of selected groups of invertebrates, birds and plants spanning the full elevational range of rainforest in the Eungella region, from approximately 200 to 1200 metres above sea level (Ashton *et al*., this volume). During these surveys, incidental collections of dragonflies and damselflies were also made in a variety of standing and flowing aquatic water bodies in both rainforest and more open habitats. Based on these collections, specimens in museum collections, and specimens and observational records obtained using the *Atlas of Living Australia* (ALA), we collate the species of dragonflies and damselflies recorded from Eungella and discuss the odonate fauna in terms of the distributions of the species and the region's biogeography.

METHODS

This paper collates records of species of dragonflies and damselflies from the broader Eungella region comprising the Eungella plateau, the upper Pioneer Valley as far east as Gargett, and the area around Eungella Dam on the western side of the Clarke Range. Specimens were collected or observed by CJB, EL, ABR and co-workers during combined Griffith University and Queensland Museum (QM) elevational surveys of the region in November 2013, January 2014 and March–April 2014. Odonata were surveyed from rainforest-fringed streams in the lowlands at Finch Hatton Gorge (21°04′S 148°38′E, 220–300 m above sea level (asl)) and Owens Creek (21°04′S 148°41′E, 150–200 m asl). Open habitats in the lowlands were surveyed at Cattle Creek (21°08′19″S, 148°37′47″E, 80 m asl) in the upper Pioneer Valley and Teemburra Dam (21°11′15″S 148°40′10″E, 290 m asl) and Eungella Dam (21°09′04″S 148°22′54″E, 570 m asl). On the highlands of the Eungella plateau, specimens were collected from rainforest streams along Dalrymple Road and on the track to Mt Dalrymple between 885 and 1170 m asl. Specimens were also collected in more open habitats on the plateau: along Broken River (21°10′04″S 148°32′11″E, 700 m asl) in Eungella township (21°07′47″S 148°29′41″E, 700 m asl), and a farm dam at the end of Dalrymple Road (21°02′04″S 148°35′57″E, 980 m asl). Additional specimen records in the collections of the QM were collated by CJB, and those in the Australian Museum (AM) and the Australian National Insect Collection (ANIC) were collated by GT. Three species are recorded from the region based on specimens listed in taxonomic literature (Watson, 1991; Theischinger, 1999). Finally, specimen records, and observational records of species accompanied by identifiable photographs, from the region were also sourced using the *Atlas of Living Australia* (ALA, https://www.ala.org.au last accessed 26 September 2018).

The family-level taxonomy for Zygoptera (damselflies) used in this paper largely follows the global systematic consensus of Odonata presented by Dijkstra *et al.* (2013), except that all megapodagrionids are placed in the Argiolestidae as established by Kalkman & Theischinger (2013). For the Anisoptera (dragonflies), we adopt the more recent classification presented by Carle *et al.* (2015). With respect to the Eungella dragonfly fauna, the classifications of Carle *et al.* (2015) and Dijkstra *et al.* (2013) are mostly in agreement. However, the genera *Austrocordulia* and *Cordulephya* were not assigned to any particular family by Dijkstra *et al.* (2013) and were collectively placed under (libelluloid) 'Genera *incertae sedis*', whereas they were both included within an expanded Synthemistidae by Carle *et al.* (2015).

RESULTS AND DISCUSSION

Based on our surveys, specimens in collections (AM, ANIC, QM) and published literature, and observational records obtained using the *Atlas of Living Australia*, a total of 58 species of dragonflies and damselflies representing 12 families are known from the broader Eungella region (Table 1). Dragonflies, with 37 species, outnumber damselflies with 21 species. A brief synopsis of each family is presented below, followed by a discussion of the broader affinities of the odonate fauna of the Eungella region.

Zygoptera – the damselflies

Synlestidae

Synlestids are large damselflies that rest with their wings spread, usually hanging from vegetation along the edges of streams. Two species are known from Eungella. Collections of *Synlestes selysi* from the Eungella region represent the northernmost extent of the range of the species and are highly disjunct from the nearest records from south-eastern Queensland (Bunya Mountains and rainforests of the Sunshine Coast hinterland), separated by around 700 km. The second species, *Episynlestes intermedius*, is endemic to the Eungella region where it has been collected at Finch Hatton Gorge and rainforest streams on the Eungella plateau. *Episynlestes intermedius*, as the name suggests, is intermediate in morphology between its two congeners, *E. cristatus* and *E. albicauda* (Theischinger & Watson, 1985). *Episynlestes cristatus* is restricted to the Wet Tropics bioregion of far north Queensland, separated from *E. intermedius* by the Burdekin-Lynd Barrier (=Paluma-Eungella Gap). Similarly, the St Lawrence Gap separates the range of *E. intermedius* from that of *E. albicauda* which overwhelmingly occurs in subtropical rainforests of south-eastern Queensland and north-eastern New South Wales.

TABLE 1. Dragonfly and damselfly species recorded from the Eungella region, including the upper Pioneer Valley and Eungella Dam. According to their known distributions, species have been classified as: 'endemic', occurring only in the Eungella region and the wider Clarke Range; 'southern', occurring as far north as Eungella and nearby central Queensland rainforests but not beyond the Burdekin-Lynd Barrier (BLB); 'northern', occurring as far south as Eungella but not beyond the St Lawrence Gap; and 'widespread', occurring both north and south of Eungella and often far beyond, i.e. spanning both the BLB and the St Lawrence Gap. An asterisk (*) indicates species that were collected or observed during recent (2013–2014) Queensland Museum and Griffith University surveys of the area.

SCIENTIFIC NAME	COMMON NAME	DISTRIBUTION
Suborder Zygoptera		
Family Synlestidae		
*Episynlestes intermedius**	Intermediate Whitetip	endemic
*Synlestes selysi**	Forest Needle	southern
Family Lestidae		
Austrolestes leda	Wandering Ringtail	widespread
Family Lestoideidae		
*Diphlebia coerulescens**	Sapphire Rockmaster	southern
Family Argiolestidae		
*Austroargiolestes elke**	Azure Flatwing	endemic
*Austroargiolestes icteromelas**	Common Flatwing	widespread
Family Isostictidae		
*Labidiosticta vallisi**	Large Wiretail	widespread
*Rhadinosticta simplex**	Powdered Wiretail	widespread
Family Platycnemididae		
*Nososticta solida**	Orange Threadtail	widespread
*Nososticta solitaria**	Fivespot Threadtail	widespread
Family Coenagrionidae		
*Agriocnemis argentea**	Silver Wisp	widespread
*Agriocnemis pygmaea**	Pygmy Wisp	widespread
*Argiocnemis rubescens**	Red-tipped Shadefly	widespread
*Austroagrion watsoni**	Eastern Billabongfly	widespread
Austrocnemis splendida	Splendid Longlegs	widespread
*Ischnura aurora**	Aurora Bluetail	widespread
*Ischnura heterosticta**	Common Bluetail	widespread
*Pseudagrion aureofrons**	Gold-fronted Riverdamsel	widespread
*Pseudagrion ignifer**	Flame-headed Riverdamsel	widespread
*Pseudagrion microcephalum**	Blue Riverdamsel	widespread
Xanthagrion erythroneurum	Red and Blue Damsel	widespread
Suborder Anisoptera		
Family Aeshnidae		
*Adversaeschna brevistyla**	Blue-spotted Hawker	widespread
Anax papuensis	Australian Emperor	widespread

SCIENTIFIC NAME	COMMON NAME	DISTRIBUTION
Suborder Anisoptera (*cont.*)		
Family Aeshnidae (*cont.*)		
*Austroaeschna christine**	S-spot Darner	endemic
*Austroaeschna eungella**	Eungella Darner	endemic
*Austroaeschna pinheyi**	Inland Darner	southern
*Austrophlebia costalis**	Southern Giant Darner	southern
Gynacantha rosenbergi	Grey Duskhawker	northern
Telephlebia cyclops	Northern Evening Darner	southern
Family Gomphidae		
Austroepigomphus turneri	Flame-tipped Hunter	widespread
*Austrogomphus amphiclitus**	Pale Hunter	widespread
Austrogomphus cornutus	Unicorn Hunter	widespread
Hemigomphus comitatus	Zebra Vicetail	northern
*Hemigomphus heteroclytus**	Stout Vicetail	widespread
*Ictinogomphus australis**	Australian Tiger	widespread
Family Synthemistidae		
Austrocordulia refracta	Eastern Hawk	widespread
*Choristhemis flavoterminata**	Yellow-tipped Tigertail	widespread
Cordulephya pygmaea	Common Shutwing	southern
*Eusynthemis nigra**	Black Tigertail	widespread
Family Corduliidae		
*Hemicordulia australiae**	Australian Emerald	widespread
*Hemicordulia intermedia**	Yellow-spotted Emerald	widespread
Family Libellulidae		
*Brachydiplax denticauda**	Palemouth	widespread
*Crocothemis nigrifrons**	Black-headed Skimmer	widespread
Diplacodes bipunctata	Wandering Percher	widespread
*Diplacodes haematodes**	Scarlet Percher	widespread
Diplacodes trivialis	Chalky Percher	widespread
*Hydrobasileus brevistylus**	Water Prince	widespread
*Macrodiplax cora**	Wandering Pennant	widespread
*Nannophlebia eludens**	Elusive Archtail	widespread
*Nannophlebia risi**	Common Archtail	widespread
*Orthetrum caledonicum**	Blue Skimmer	widespread
*Orthetrum migratum**	Rosy Skimmer	widespread
*Orthetrum sabina**	Slender Skimmer	widespread
*Orthetrum villosovittatum**	Fiery Skimmer	widespread
*Pantala flavescens**	Wandering Glider	widespread
*Rhyothemis graphiptera**	Graphic Flutterer	widespread

SCIENTIFIC NAME	COMMON NAME	DISTRIBUTION
Suborder Anisoptera (*cont.*)		
Family Corduliidae (*cont.*)		
*Rhyothemis phyllis**	Yellow-striped Flutterer	widespread
*Tramea loewii**	Common Glider	widespread

Lestidae

The family Lestidae is more diverse in southern Australia, and only the widespread, standing water-breeding *Austrolestes leda* has been recorded from the Eungella region, although a couple of other lestid species are likely to occur there.

Lestoideidae

This family is represented in the region by a single species, *Diphlebia coerulescens*, one of five species of robust rockmaster damselflies of the genus *Diphlebia* that inhabit streams and rivers of eastern Australia. In the Eungella region, *D. coerulescens* occurs from the lowlands (Owens and Cattle Creeks) to the highlands of Eungella plateau, inhabiting streams in rainforest and more open habitats. There are more northerly records of *Diphelbia coerulescens* from Cathu State Forest, still within the Clarke Range, about 40 km north of the township of Eungella. However, in the Wet Tropics bioregion this species is replaced by the closely allied *Diphlebia euphaeoides*. As with *Synlestes selysi*, there is a substantial gap in the known range of *D. coerulescens*, with around 700 km separating collection records from the Eungella region from the nearest more southerly records from the Conondale Range in the Sunshine Coast hinterland.

Argiolestidae

There are ten described species in the genus *Austroargiolestes* which is endemic to eastern Australia. Two species with very different distributional ranges are known from the Eungella region. *Austroargiolestes icteromelas* is the most widespread species in the genus, occurring from the Wet Tropics bioregion to southern Victoria. In the Eungella region it occurs along streams from low elevations (Owens Creek and Finch Hatton Gorge) to the highlands of the Eungella plateau. In contrast, *Austroargiolestes elke* is endemic to the Eungella region and arguably has the smallest range of any species in the genus. It is known from a handful of collections from rainforest at Finch Hatton Gorge, Quandong Creek along the Dalrymple Road, and near Mt Dalrymple.

Isostictidae

The family is represented in the region by two relatively widespread species, *Rhadinosticta simplex* and *Labidiosticta vallisi*. Recorded from the Eungella region for the first time in our recent surveys, both species were collected from Broken River, and *L. vallisi* was also collected from Owens Creek. Both species have also been recorded from slightly farther north in the Clarke Range from Cathu State Forest.

Platycnemididae

Two species of *Nososticta*, the only genus of Platycnemididae represented in Australia, are known from the Eungella region, *N. solida* and *N. solitaria*. Both inhabit streams and rivers, including riverine pools. On our recent surveys, both species were collected at low to mid-elevations and occurred together in streams in more open habitats such as at Broken River and Cattle Creek, whereas only *N. solitaria* was collected from streams in rainforest at Finch Hatton Gorge and Owens Creek.

Coenagrionidae

This is the most speciose family of damselflies worldwide, in Australia and in the Eungella region. Most species in the region inhabit standing water habitats, including small farm dams and larger lakes, riverine pools along sluggish streams, and pools on the edges of faster-flowing streams. The Eungella fauna includes two species of *Agriocnemis* (*argentea* and *pygmaea*), *Argiocnemis rubescens*, *Austroagrion watsoni*, *Pseudagrion microcephalum*, *Xanthagrion erythroneurum*, and two very widespread species of *Ischnura* (*aurora* and *heterosticta*). Two other coenagrionids, *Pseudagrion ignifer* and *P. aureofrons*, are inhabitants of flowing streams and rivers in more open habitats, whereas *P. microcephalum* also inhabits very slow-flowing streams and rivers.

Anisoptera – the dragonflies

Aeshnidae

Eight species of aeshnids have been recorded from the Eungella region. Of the three species in the subfamily

Aeshninae, two are widespread. *Anax papuensis* is found throughout Australia, while *Adversaeschna brevistyla* is widespread in southern Australia with few records from the tropics. The only record of *A. brevistyla* from the region is a single female collected from a farm dam at the end of the Dalrymple Heights road during our recent surveys. The other aeshnine known from the region, the crepuscular *Gynacanthaa rosenbergi*, is represented by a single female extracted alive from the grille of a Queensland Parks and Wildlife Service (QPWS) vehicle at Eungella township. *Gynacantha rosenbergi* has been recorded from the Top End of the Northern Territory, and northern Queensland as far south as the southern Wet Tropics bioregion (Theischinger & Endersby, 2009) and, as far as we are aware, this is the only record of the species south of the Burdekin-Lynd Barrier. The QPWS vehicle had been driven from Finch Hatton Gorge to Eungella in the early evening (Harry Hines *pers. comm.*), and almost certainly the specimen had been hit somewhere in the warmer lowlands of the upper Pioneer Valley. *Gynacantha rosenbergi* is very similar to *G. dobsoni*, and we have identified the female specimen as the former species based on the broad ventral regions of its third abdominal tergite, as per the key in Theischiner & Endersby (2009). However, the reliability of this character in separating females of the two species needs further examination and, as such, our identification is provisional at this time.

The five remaining aeshnid species, *Austrophlebia costalis*, *Telephlebia cyclops* and three species of *Austroaeschna*, are included in the subfamily Telephlebiinae, a group with Gondwanan affinities. *Austrophlebia* includes two species of enormous dragonflies that inhabit rainforest streams in eastern coastal Australia. The Eungella region is the northernmost extent of the range of *A. costalis*, which otherwise occurs from eastern Victoria and New South Wales to south-eastern Queensland. The nearest known records to those from Eungella are from the Bunya Mountains and the hinterland of the Sunshine Coast. This species is replaced in the Wet Tropics by *Austrophlebia subcostalis*. *Telephlebia* includes six described species. *Telephlebia cyclops* is known from north-eastern New South Wales and south-eastern Queensland, with apparently isolated, more northerly populations at Kroombit Tops south-west of Gladstone and Eungella.

Of the three species of *Austroaeschna* recorded from Eungella, *A. christine* and *A. eungella* are apparently restricted to rainforests of the Clarke Range. To date, *A. christine* has only been collected from Finch Hatton Gorge and the Eungella plateau, where it occurs together with *A. eungella* which has also been collected from Cathu State Forest slightly further north. Both species are most closely related to congeners found in south-eastern Queensland and further south (Theischinger, 1993). *Austroaeschna christine* is most similar to *A. sigma* which extends south to the central coast of New South Wales, and *A. eungella* is most similar to *Austroaeschna pulchra* which extends as far south as Victoria. The third species of *Austroaeschna* from the region is known only from two specimens collected on the recent Eungella Biodiversity Survey, one from Broken River and another from Owens Creek. These specimens appear to be *Austroaeschna pinheyi*, a species mainly known from southern inland Queensland (e.g. Carnarvon Range).

Gomphidae

The family Gomphidae is represented in the Eungella region by two species of *Hemigomphus*, two species of *Austrogomphus*, one species of *Austroepigomphus* and one species of *Ictinogomphus*. In the Eungella region, *Hemigomphus heteroclytus* is common along rocky streams running through rainforest and more open habitats, and occurs in both the lowlands and higher elevations. This species occurs both north and south of the region, extending into the Wet Tropics and occurring as far south as Victoria and South Australia. In contrast, *Hemigomphus comitatus* is widespread in the Wet Tropics bioregion, with a single collection from Finch Hatton Gorge in the Eungella region representing the southernmost extent of its range. *Austroepigomphus turneri* occurs across northern Australia from the Kimberley region in Western Australia across the Top End of the Northern Territory, and from Cape York Peninsula along the east coast of Queensland south to about Rockhampton. In the Eungella region it is known from a single collection from Dalrymple Creek in the lowlands (Watson, 1991). Of the two species of *Austrogomphus* recorded from the Eungella region, *A. amphiclitus* appears to be much more common and has been collected from Broken River, Cattle Creek and Owens Creek, and also from Cathu State Forest further north in the Clarke Range. There is only a single record of the second species, *Austrogomphus cornutus*, from the region from "Dalrymple Creek, Finch Hatton" (Watson, 1991). In Australia, the genus *Ictinogomphus* is represented by three species, with only the widespread *I. australis* known from the Eungella region with records from Cattle Creek and Eungella Dam.

Synthemistidae

Four species of Synthemistidae are known from the Eungella region. *Choristhemis flavoterminata* is widespread in eastern Australia from the Wet Tropics to the border of Victoria and New South Wales, and has been collected from streams at mid- to low elevations in the Eungella region: Broken River, Cattle Creek and Owens Creek. *Eusynthemis nigra* occurs from the Wet Tropics to north-eastern New South Wales. Two subspecies are recognised, *E. nigra nigra* found north of the Burdekin-Lynd Barrier and *E. nigra xanthosticta* to the south. Specimens *E. n. xanthosticta* from south-eastern Queensland differ in coloration from those of *E. n. nigra* from the Wet Tropics, the former having more extensive yellow markings on the metepimeron and generally showing greater variability in body coloration. Specimens from the Eungella region are considered to be *E. n. xanthosticta*. However, they show variation in the extent of yellow markings on the metepimeron, and some appear closer than others to the 'typical' condition seen in the less variable nominate subspecies. In the region, specimens have been collected from both low and high elevations and as far north as Cathu State Forest.

In the Eungella region, *Austrocordulia refracta* is represented by a single collection of a larval exuvium from low elevation at Dalrymple Creek (Theischinger, 1999) at Mount Charlton, slightly north of Owens Creek. This species, widely distributed in eastern coastal mainland Australia, is likely to be more widespread in the Eungella region as it is encountered uncommonly due to its crepuscular habits. Similarly, *Cordulephya pygmaea* is known from only two collections from the region, one from the 'Eungella Range' and one from Broken River, which represent the northernmost extent of its known distribution. The species is otherwise known to occur from Victoria through eastern New South Wales to south-eastern Queensland, with another isolated record from Carnarvon Gorge. More specimens of *Cordulephya* from the isolated populations at Carnarvon Gorge and Eungella are required to assess if they are indeed conspecific with those from southern Australia.

Corduliidae

Two species of *Hemicordulia* have been recorded from the Eungella region, with a single collection of *H. intermedia* from Dalrymple Creek. There are more records of the *H. australiae*, with collections from Broken River and the Eungella plateau.

Libellulidae

This family is the most speciose worldwide and in Australia, as well as in the Eungella region where seventeen species have been recorded. Additional species are likely to occur there. The majority of these species are widespread and associated with standing or sluggish-flowing water habitats such as lakes, ponds and riverine pools. A few species, however, are associated with faster-flowing streams such as two species of *Nannophlebia*, *N. risi* and *N. eludens*, both of which are found along streams at lower elevations in the region. *Diplacodes haematodes* also occurs along streams but prefers backwaters and rockpools.

General Discussion

Although located within the tropics, floristically the upland rainforests of the Eungella plateau and the broader Clarke Range are northern outliers of the subtropical rainforests of south-eastern Queensland and north-eastern New South Wales. This is also reflected by many faunal groups, both invertebrate and vertebrate, which feature subtropical rainforest species with disjunct populations in the highlands of the Clarke Range that represent the northernmost extent of their geographical ranges (see for example Mahony (this volume) for frogs, Leach *et al*. (this volume) for birds, Burwell *et al*. (this volume) for ants). This is also the case for the odonate fauna, where Eungella and nearby central Queensland rainforests are the northernmost extent of the distribution of a number of rainforest species that otherwise occur in subtropical Queensland and farther south. These include *Telephlebia cyclops* and *Austroaeschna costalis* among the dragonflies, and *Synlestes selysi* and *Diphlebia coerulescens* among the damselflies. Two other dragonflies, *Cordulephya pygmaea* and *Austroaeschna pinyhei*, also show this distribution pattern but occur in more open habitats rather than rainforest. The northern populations of some of these species are highly disjunct, separated from their nearest known collection localities in south-eastern Queensland by around 700 km. *Telephlebia cyclops*, however, is known from Kroombit Tops in the intervening region, about 450 km south-east of Eungella, and targeted collecting there and in other patches of subtropical rainforest such as the Many Peaks Range may fill in the large gaps in our knowledge of the distributions of some of these species.

Watson and Theischinger (1984) identified the gap in the Great Dividing Range between the Eungella region and the Paluma Range in the southern Wet

Tropics bioregion as one of a number of areas of 'taxonomic disjunction' for the Australian odonate fauna and other groups of freshwater insects. This 'gap' of low topography and drier open forests separates the rainforests of the Wet Tropics from those of the Central Queensland Coast (CQC). It has long been recognised as a significant biogeographic barrier for the dispersal of rainforest-dependent fauna and is known as the Burdekin-Lynd Barrier (Keast, 1961), referred to as the BLB hereafter. The four rainforest species listed above, for example, do not cross this barrier, and are replaced by closely related congeners in the rainforests of the Wet Tropics north of the barrier. These southern and northern species-pairs that occur on either side of the BLB are *Austrophlebia costalis* and *A. subcostalis*, *Diphlebia coerulescens* and *D. euphaeoides*, *Telephlebia cyclops* and *T. tillyardi* (which is actually closer to *T. tryoni* and *T. undia* from further south), and *Synlestes selysi* and *S. tropicus*. Curiously, there appear to be only two examples of species that show the opposite trend in their distributions, namely *Hemigomphus comitatus* and *Gynacantha rosenbergi*. The former, a stream-dwelling gomphid, is largely confined to the Wet Tropics and is known from a single collection from Finch Hatton Gorge on the southern side of the BLB and has not been recorded further south. Similarly, the specimen of *G. rosenbergi* from the Eungella region is the only record of the species from south of the BLB.

The rainforests of the CQC are also separated from the subtropical rainforests of south-eastern Queensland by a low topography barrier of drier forests, the St Lawrence Gap. This biogeographic barrier appears to have had less influence on rainforest Odonata than the BLB, but their combined influence is likely responsible for the most distinctive element of the Eungella fauna, the four species endemic to the rainforests of the Central Queensland Coast: *Episynlestes intermedius*, *Austroargiolestes elke*, *Austroaeschna christine* and *Austroaeschna eungella*. All four species have closely related congeners in the subtropical rainforests to the south and, in some instances, counterparts in the Wet Tropics to the north. All four are confined to rainforests, usually at higher elevations, but most have also been collected as low as Finch Hatton Gorge where temperatures are perhaps lower than might be expected due to downslope movement of cooler air and less insolation due to increased shading in the gorge.

The majority of the species found in the Eungella region are widespread species that extend from northern to southern Queensland, across the BLB and the St Lawrence Gap, and often far beyond. Many of these species prefer open habitats and breed in standing waters. This applies to the single lestid and most of the coenagrionid species among the damselflies, and dragonfly species in the families Corduliidae, Aeshnidae (*Anax* and *Adversaeschna*), Gomphidae (*Ictinogomphus*), as well as most of the libellulids. Some stream-dwelling species found in the region are also widespread. Among the damselflies these include *Austroargiolestes icteromelas*, species of *Nososticta* and *Pseudagrion*, and the two isostictids. Widespread stream-dwelling dragonflies include most of the synthemistid and gomphid species, and *Diplacodes haematodes* and the two species of *Nannophlebia* among the libellulids. Many additional species of widespread dragonflies and damselflies are expected to occur in the Eungella region but have yet to be reliably recorded there.

Although the Eungella region, as defined above, has been moderately well collected, the wider Clarke Range and particularly other rainforest areas of the Central Queensland Coast have been poorly surveyed for dragonflies and damselflies. Apart from some collections in Cathu State Forest about 40 km north of the township of Eungella, the northern part of the Clarke Range has been little sampled and the wider distribution of the endemic species that appear confined to the Clarke Range is unknown. Other mountain ranges in the CQC with at least some rainforest are virtually unsurveyed, including the Connors Range west of Sarina, the Conway Range east of Proserpine, and the area surrounding Mt Dryander north of Proserpine. As noted above, many additional widespread dragonfly and damselfly species are expected to occur in the Eungella region. Using the *Atlas of Living Australia*, a search for odonate records from the mainland encompassing Proserpine in the north, Sarina in the south and Eungella Dam in the west revealed reliable records of 16 species in addition to those recorded from the Eungella region. The list of species presented here for the Eungella region is likely to be conservative and far from complete.

ACKNOWLEDGEMENTS

Eungella fieldwork undertaken in 2013 and 2014 as part of the Eungella Biodiversity Survey was funded by Griffith University and the Mackay Regional Council, and led by Roger Kitching, Aki Nakamura and Louise Ashton. We thank our colleagues who assisted with the collection of dragonflies and damselflies. Thanks also to Harry Hines (Queensland Parks and Wildlife Service) for supplying recently collected specimens of Common Shutwing and Grey Duskhawker from Eungella. Thanks also to Karin Koch for her assistance in collating specimen records from the Queensland Museum.

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RAINFOREST ANTS (HYMENOPTERA: FORMICIDAE) ALONG AN ELEVATIONAL GRADIENT AT EUNGELLA IN THE CLARKE RANGE, CENTRAL QUEENSLAND COAST, AUSTRALIA

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Here we provide a faunistic overview of the rainforest ant fauna of the Eungella region, located in the southern part of the Clarke Range in the Central Queensland Coast, Australia, based on systematic surveys spanning an elevational gradient from 200 to 1200 m asl. Ants were collected from a total of 34 sites located within bands of elevation of approximately 200, 400, 600, 800, 1000 and 1200 m asl. Surveys were conducted in March 2013 (20 sites), November 2013 and March–April 2014 (24 sites each), and ants were sampled using five methods: pitfall traps, leaf litter extracts, Malaise traps, spraying tree trunks with pyrethroid insecticide, and timed bouts of hand collecting during the day. In total we recorded 142 ant species (described species and morphospecies) from our systematic sampling and observed an additional species, the green tree ant *Oecophylla smaragdina*, at the lowest elevations but not on our survey sites. With the caveat of less sampling intensity at the lowest and highest elevations, species richness peaked at 600 m asl (89 species), declined monotonically with increasing and decreasing elevation, and was lowest at 1200 m asl (33 spp.). Ant species composition progressively changed with increasing elevation, but there appeared to be two gradients of change, one from 200–600 m asl and another from 800 to 1200 m asl. Differences between the lowland and upland faunas may be driven in part by a greater representation of tropical and arboreal-nesting species in the lowlands and a greater representation of subtropical species in the highlands. We briefly overview the Eungella ant fauna of each subfamily and make comparisons with ants collected from surveys along comparable elevational gradients at Lamington National Park in subtropical south-eastern Queensland, and Mt Lewis in the Wet Tropics bioregion of northern Queensland.

Keywords: ants, Formicidae, Eungella

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INTRODUCTION

As part of a broader research program investigating the distributions of rainforest invertebrates and plants along gradients of elevation in eastern Queensland, we sampled ants in the rainforests of the Eungella region, referred to as Eungella hereafter. Located about 60–70 km west of the city of Mackay, Eungella is situated within the Central Queensland Coast (CQC), the region extending from just north of the town of Proserpine to south of Sarina. The rainforests of the CQC are biogeographically isolated from the rainforests of the Wet Tropics region to the north by the Burdekin-Lynd Barrier, a corridor of low-elevation, drier forests. Similarly, another biogeographic barrier to the south, the St Lawrence Gap, separates the rainforests of the CQC from a chain of subtropical rainforest patches in south-eastern Queensland and north-eastern New South Wales. The Clarke Range contains the greatest extent of upland rainforests in the CQC, and the highest-elevation rainforests occur in the Eungella region in the southern Clarke Range.

There has been no published overview of the ant fauna of Eungella, but information on the ant species of the region is scattered throughout the taxonomic literature. It was not our intention to review comprehensively this literature for records of species from Eungella. However, the significance of the ant fauna of the region's upland rainforests is apparent since it contains both endemic species (Ogata & Taylor, 1991) and disjunct populations of more southerly species (e.g. see Taylor, 1977; Shattuck, 2015). Instead, here we provide an overview of Eungella's fauna of rainforest ants based on extensive surveys at 34 sites spanning an elevational gradient encompassing almost the entire extent of rainforest in the region, from 200 to 1200 m above sea level. We also compare the ants collected from our Eungella gradient with collections of ants made along similar elevational gradients in the subtropical rainforests of south-eastern Queensland and the tropical rainforests of the Wet Tropics bioregion of far northern Queensland.

METHODS

Study Design

We sampled ants from rainforests in the Eungella region (21.1°S) from sites spanning a gradient of elevation from 200 to 1200 m above sea level (asl). Four to seven sites were established within bands of elevation separated by around 200 vertical metres. Owing to the difficulties of working in mountainous terrain and locating suitable habitat, the elevations of sites within each band varied. The mean elevation of sites within each band, however, was always within ±10 vertical metres of the desired elevation. An average decrease of 0.6°C per 100 m increase in elevation occurred along the Eungella transect, based on data collected in December 2014 to February 2015 using iButtons™.

Ant sampling was conducted on three separate survey periods: 4–26 March 2013, 4–30 November 2014, and 15 March–12 April 2014. In March 2013, ants were sampled from five sites in each of four bands of elevation: approximately 400, 600, 800 and 1000 m asl. All sites were within Eungella National Park. Sites at 400 and 600 m asl were situated close to Finch Hatton Gorge, sites at 800 m asl were along the road between Eungella township and Broken River in the vicinity of the Sky Window Picnic Area, and sites at 1000 m asl were located along the Mt Dalrymple Road and the beginning of the walking track to Mt Dalrymple. In November 2013 and March to April 2014, ants were sampled from four sites in each of six bands of elevation: approximately 200, 400, 600, 800, 1000 and 1200 m asl. These two later surveys re-sampled four of the five sites at 1000 m asl established in March 2013. Due to the close proximity of some sites established at 400, 600 and 800 m asl (closest distance between sites was 100 m, 90 m and 190 m, respectively) in March 2013, only two of the five sites at each elevation were re-sampled in the two later surveys. Instead, two new sites were established at each of 400 and 600 m asl near Owens Creek in Pelion State Forest, as were new sites at 800 m asl along Diggings Road and Dalrymple Road. In addition, four sites at 200 m asl, one at Finch Hatton Gorge and three along Owens Creek in Pelion State Forest, were sampled, as were four sites at 1200 m asl: two on or close to Mt William, one on Mt Dalrymple and another along the walking track to Mt Dalrymple, all in Eungella National Park. Thus, in total, four unique sites were sampled at 200 and 1200 m asl, five sites at 1000 m asl, and seven at 400, 600, and 800 m asl (Table 1). Individual sites were sampled one, two or three times, as indicated in Table 1. As a result, there was variation among elevational bands in the total number of site surveys (the product of the number of unique sites and how often each was surveyed): 200 m asl and 1200 m asl, eight total site surveys; 400, 600, 800 and 1000 m asl, 13 site surveys.

TABLE 1. Summary of actual elevations and latitude and longitude co-ordinates of Eungella survey sites arranged by elevational bands. Also indicated are which sites were sampled in the three survey periods: *March 2013*, 4–26 March 2013; *November 2013*, 4–30 November 2014; *March–April 2014*, 15 March–12 April 2014, and the total number of samples collected at each site.

Elevational band – site	Latitude (°S)	Longitude (°E)	Elevation (m asl)	March 2013	November 2013	March–April 2014	No. samples
200 – 1	21.0766	148.6878	194		X	X	2
200 – 2	21.0746	148.6849	178		X	X	2
200 – 3	21.0764	148.6793	212		X	X	2
200 – 4	21.0673	148.6351	251		X	X	2
400 – 1	21.0619	148.6358	373	X	X	X	3
400 – 2	21.0611	148.6348	397	X			1
400 – 3	21.0614	148.6369	371	X			1

Elevational band – site	Latitude (°S)	Longitude (°E)	Elevation (m asl)	March 2013	November 2013	March–April 2014	No. samples
400 – 4	21.0605	148.6376	390	X	X	X	3
400 – 5	21.0597	148.6370	431	X			1
400 – 6	21.0702	148.6865	374		X	X	2
400 – 7	21.0655	148.6830	432		X	X	2
600 – 1	21.0564	148.6353	575	X	X	X	3
600 – 2	21.0556	148.6352	591	X			1
600 – 3	21.0556	148.6364	595	X			1
600 – 4	21.0548	148.6355	615	X	X	X	3
600 – 5	21.0539	148.6366	657	X			1
600 – 6	21.0634	148.6792	580		X	X	2
600 – 7	21.0623	148.6772	628		X	X	2
800 – 1	21.1447	148.4981	778	X			1
800 – 2	21.1431	148.4970	772	X	X	X	3
800 – 3	21.1429	148.4947	775	X			1
800 – 4	21.1413	148.4939	769	X	X	X	3
800 – 5	21.1491	148.5025	776	X			1
800 – 6	21.1218	148.5033	854		X	X	2
800 – 7	21.1438	148.4891	858		X	X	2
1000 – 1	21.0589	1485818	1022	X	X	X	3
1000 – 2	21.0512	148.5806	998	X	X	X	3
1000 – 3	21.0358	148.5970	1002	X	X	X	3
1000 – 4	21.0350	148.6003	988	X	X	X	3
1000 – 5	21.0302	148.6035	971	X			1
1200 – 1	21.0169	148.5980	1234		X	X	2
1200 – 2	21.0151	148.6084	1172		X	X	2
1200 – 3	21.0262	148.6274	1169		X	X	2
1200 – 4	21.0256	148.6384	1232		X	X	2

Ant Sampling

At each site a central 20 m × 20 m quadrat was established, where most ant sampling was conducted.

The same sampling methodology was employed at each site over the three survey periods: March 2013, November 2014, and March–April 2014. Five methods were used to sample the ant fauna of each site: leaf litter extraction ('litter extracts'), spraying tree trunks with insecticide ('bark sprays'), Malaise traps, pitfall traps, and timed hand collecting during the day ('day hand'). Samples were collected within the central quadrat of each site except for day hand samples. Each litter extract (two per site per survey) was derived from 1 m^2 of sifted leaf litter processed in a Tullgren funnel for 24–36 hours (wetter litter was extracted for longer). For each bark spray sample (two per site per survey), the trunks of five large trees (>30 cm dbh) were sprayed using hand-held cans of Mortein Fast Knockdown® pyrethroid insecticide. Falling insects were collected on a rectangular sheet of rip-stop at the base of each tree, and after around 15 minutes the catches on the five sheets were transferred to an ethanol-filled vial using a suspended fabric funnel. A single day hand sample was collected per site per survey, where CJB searched for foraging ant workers and ant nests for 60 minutes within a 40–50 m radius of the centre of the quadrat, between 0905 and 1650 hours. Not all observed ants were collected; rather, the aim was to maximise the number of species collected. Ten pitfall traps were established at each site and operated for ten days. Traps were 42 mm internal diameter, 120 ml plastic vials half filled with 95% ethanol, with a square, black plastic rain cover suspended 3–4 cm above the opening. The ten traps were arranged in a line spanning one of the diagonals of the site quadrat (traps 2.5–3.0 m apart). A single Townes-type Malaise trap was operated for 10 days at each site. More detailed descriptions of the sampling methods can be found in Burwell & Nakamura (2016).

Sorting and Identification

Worker ants were extracted from all samples and identified to genus and morphospecies or described species (collectively referred to as 'species' hereafter) by CJB. The only exception was in the genus *Solenopsis*, represented by minute litter-inhabiting thief ants, where we did not attempt to divide our specimens into morphospecies. Identification of species of *Solenopsis* is notoriously difficult, and the presence of cryptic species is possible as has been demonstrated along a 2000 m elevational gradient in the Ecuadorian Andes (Delsinne *et al.*, 2012). A voucher collection of pinned representatives of all species is deposited in the Queensland Museum. Subfamily, generic and species-level classification largely follows that adopted by the Australian Faunal Directory (https://biodiversity.org.au/afd/taxa/FORMICIDAE/checklist, last accessed 28 October 2018), except for relatively recent taxonomic developments. *Colobopsis* is treated as a valid genus distinct from *Camponotus* (Ward *et al.*, 2016), and *Machomyrma* is treated as a synonym of *Pheidole* (Ward *et al.*, 2015). For many genera, species collected along the Eungella gradient were compared and matched with species collected along two other rainforest gradients of elevation in Queensland, one at Lamington National Park (28.1°S) in subtropical south-eastern Queensland and one in tropical northern Queensland at Mt Lewis (16.3°S) in the Carbine Uplands subregion of the Wet Tropics. At the Mt Lewis gradient, four sites at each of five elevational bands (400, 600, 800, 1000 and 1200 m asl) were sampled once in March 2012 using the same sampling protocol used at Eungella (see Burwell & Nakamura, 2016 for more details). At the Lamington gradient, four sites at each of five elevational bands (300, 500, 700, 900 and 1100 m asl) were sampled three times in October 2006, March 2007 and January 2008) using the same methods used at Eungella. We place more emphasis on comparisons between the Eungella and Lamington gradients as the sampling intensity at each was relatively similar. We also comment on the known extent of the distribution of particular ant species. This information is drawn either from the taxonomic literature or through examination of distribution records accessed using online resources: *Atlas of Living Australia* (ALA, https://www.ala.org.au/) and *Antmaps* (http://antmaps.org/; Janicki *et al.*, 2016).

Data Analysis

In this study, a sample consisted of specimens collected from a given site at a given survey period. The total number of samples in each elevational band therefore varied between eight and thirteen (Table 1). Data from all five collecting methods were pooled for each sample and species abundances transformed to incidences (presence/absence). We first summarised the elevational distributions of species along the Eungella gradient. For each elevational band we summed the number of samples from which a species was recorded. We then expressed that value as a percentage of the total number of samples for that particular elevational band (Table 1). In addition, we collated the total numbers of species collected within each elevational band.

We visualised patterns of ant species composition among sites by generating a non-metric multidimensional scaling (NMDS) ordination using PRIMER 6 software. Each point on the NMDS ordination corresponded to an individual sample (i.e. 8 samples for 200 and 1200 m asl bands, and 13 samples for 400, 600, 800 and 1000 m asl bands). The ordination was generated based on a Sørensen similarity matrix and 100 random restarts.

RESULTS AND DISCUSSION

In total, we recorded at least 142 ant species across our survey sites spanning the entire gradient of elevation (Table 2). We also observed green tree ants, *Oecophylla smaragdina*, in the riparian rainforest along Owens Creek, although this species was not collected from any of our survey sites, bringing the total ant fauna to at least 143 species. These species represented 62 genera from all 12 subfamilies currently recognised and recorded from Australia (Table 3). Some of the mid-elevation sites consisted of rainforest understorey with a eucalypt canopy. This may have resulted in the collection of a small number of ant species typically found in more open habitats; *viz.* the species of *Cardiocondyla*, *Opisthopsis* and *Polyrhachis ornata* and *Polyrhachis erato* (see Table 2).

With the caveat of unequal sampling effort across the elevational gradient (fewer surveys and unique sites at 200 and 1200 m asl, and fewer sites at 1000 m asl), species richness was highest at mid-elevations, 89 species at 600 m asl, and declined as elevation both increased and decreased (Figure 1). The lowest number of species, 33, was recorded at the highest elevation, 1200 m asl, followed by 46 species at 1000 m asl (Figure 1). In terms of species composition, we found progressive turnover in ant assemblages with increasing elevation (Figure 2). There appeared, however, to be two different gradients of turnover, one in the lowlands from 200 to 600 m asl and another in the highlands from 800 to 1200 m asl (Figure 2).

TABLE 2. List of ant species collected during elevational surveys of rainforest in the Eungella region. Three surveys were conducted: March 2013 (five sites at each of four bands of elevation at approximately 400, 600, 800 and 1000 m above sea level (asl); and November 2013 and March–April 2014 (four sites at each of six bands of elevation at approximately 200, 400, 600, 800, 1000 and 1200 m asl). Shading indicates the bands of elevation where species were recorded; density of shading reflects the percentage of the total number of samples that a species was recorded. Shading reflects 10% increments from the palest (>0–10%) to the darkest (>90–100%), viz.:

>0–10	>10–20	>20–30	>30–40	>40–50	>50–60	>60–70	>70–80	>80–90	>90–100

Total possible samples from which a species could be recorded at each elevation were 13 for 400, 600, 800 and 1000 m bands, and 8 for the 200 and 1200 m bands (see Table 1).

SUBFAMILY ***Species***	**Elevational band (metres asl)**					
	200	**400**	**600**	**800**	**1000**	**1200**
AMBLYOPONINAE						
Amblyopone australis	▒	▒	▒	▒	▓	█
Amblyopone hackeri					▒	
Onychomyrmex QM.1					░	
Onychomyrmex QM.2			▒			
Onychomyrmex QM.3		░		▒		▒
Onychomyrmex sp. A	▒					
Prionopelta robynmae			▒			
DOLICHODERINAE						
Anonychomyrma QM.3				▒	█	█
Anonychomyrma QM.4	█	█	█	▓	▒	░
Anonychomyrma QM.5	▓	▒				
Anonychomyrma QM.8	▒					
Anonychomyrma QM.9			▒	▒	▒	
Iridomyrmex calvus		░	░			
Leptomyrmex mjobergi	▒	▓	▒			
Leptomyrmex rufipes		▒	▒	▒		
Ochetellus sp. C						
Tapinoma QM.2	▒		░	▒	░	

SUBFAMILY ***Species***	**Elevational band (metres asl)**					
	200	**400**	**600**	**800**	**1000**	**1200**
Tapinoma QM.3	░	░				
Tapinoma QM.4	░		░			
Technomyrmex jocosus	▒	▓	▓	▓	█	▓
Turneria bidentata	░	░	░			
DORYLINAE						
Lioponera sp. A (*turneri* group)	▒	░	▒	░	░	▒
Zasphinctus ?duchaussoyi			░			
Zasphinctus ?steinheili			░	░		▒
Zasphinctus turneri	░					
ECTATOMMINAE						
Rhytidoponera chalybaea					█	█
Rhytidoponera impressa				▓		
Rhytidoponera QM.12	▓	█				
Rhytidoponera QM.14		░	▒	▒		
Rhytidoponera victoriae	▒	▓	▓			
FORMICIDAE						
Acropyga acutiventris			▒			
Acropyga pallida				░		
Camponotus dorycus confusus						
Camponotus sp. A	▓	▒	▓	▒	░	
Camponotus sp. B		▒	▒	▒		
Camponotus sp. C	▓	▓				
Colobopsis sp. D	▒	▒	▒		░	░
Colobopsis sp. F		░				
Colobopsis vitrea		░				
Echinopla turneri	▒					
Myrmecorhynchus emeryi				▒	█	█
Notoncus sp. nov.						▒
Notostigma carazzii				░		
Nylanderia QM.1	█	█		█	▒	
Oecophylla smaragdina	0					
Opisthopsis pictus			░			
Paraparatrechina QM.4	▓	▒	▒	▒	▒	▒
Paraparatrechina QM.9		▒	▓			

SUBFAMILY ***Species***	**Elevational band (metres asl)**					
	200	**400**	**600**	**800**	**1000**	**1200**
Polyrhachis (Campomyrma) sp. nov.	░	░				
Polyrhachis (Campomyrma) maculata					░	
Polyrhachis (Cyrtomyrma) mackayi	░	░	░			
Polyrhachis (Cyrtomyrma) pilosa	░					
Polyrhachis (Hedomyrma) sp. nov	░	░	░			
Polyrhachis (Hedomyrma) argentosa	░					
Polyrhachis (Hedomyrma) clio		░				
Polyrhachis (Hedomyrma) erato		░	░			
Polyrhachis (Hedomyrma) ornatus			░			
Polyrhachis (Hedomyrma) rufifemur		░				
Prolasius formicoides		█	█	▓	█	▒
Prolasius convexus					▒	
Pseudonotoncus hirsutus			░			
Stigmacros major		▓	▒			
HETEROPONERINAE						
Heteroponera crozieri				░		
Heteroponera sp. A (*imbellis*-grp)	░	▒	░		▒	█
LEPTANILLINAE						
Leptanilla swani			░	░		
MYRMECIINAE						
Myrmecia eungellensis					█	▓
Myrmecia nigrocincta	░	▒	▒			
MYRMICINAE						
Aphaenogaster pythia	░		░			
Calyptomyrmex fragarus	░	▓	▓			
Cardiocondyla sp. A		░				
Carebara sp. A	▓	▓	▓	▓	▒	
Carebara sp. B	▓	▒	▓	▒	▒	
Carebara sp. C			░			
Colobostrum australis						░
Colobostruma leae					▓	
Colobostruma sisypha	░					
Crematogaster sp. A	▓	░	▒	█	▓	▒
Crematogaster sp. B	░	░				

SUBFAMILY *Species*	**Elevational band (metres asl)**					
	200	**400**	**600**	**800**	**1000**	**1200**
Crematogaster sp. C	▒	▒	▒			
Crematogaster sp. D	▒	▒				
Crematogaster sp. E	▒		░			
Eurhopalothrix australis		▒	░	░		
Lordomyrma sp. A	▒	▒	▒	▒		
Mayriella abstinens	▒	░	░			
Mayriella overbecki				▒		
Mayriella spinosior	▒	░	░			
Meranoplus hirsutus		▓	▒			
Monomorium kiliani						░
Monomorium 'leae'				▒	▓	█
Monomorium near *intrudens*	░					
Monomorium nigriceps	░	░		▒		▒
Monomorium sp. B	▓	▒	▒			
Monomorium sp. D	░	░	░			
Monomorium tambourinense	▒	▒		▒	░	░
Myrmecina difficulta			▒	▓	▒	▒
Myrmecina inaequala	░	▒	░			
Orectognathus mjobergi			░			
Orectognathus parvispinus		░	░	▒		
Orectognathus near *coccinatus*		░	░			
Orectognathus versicolor					▒	▓
Pheidole dispar					░	
Pheidole sp. A	█	█	█	█	█	
Pheidole sp. B	█	█	█			
Pheidole sp. C	▒	░	░	█	█	▓
Pheidole sp. D	█	█	█	█	█	░
Pheidole sp. E					█	█
Pheidole sp. F	█	█	▓			
Podomyrma sp. A			░			░
Podomyrma sp. B (*novemdentata*-grp)		░				
Podomyrma sp. C (*turneri*-grp)	░			▒		
Podomyrma basalis	▒					
Podomyrma sp. E (*novemdentata*-grp)		░				

SUBFAMILY ***Species***	**Elevational band (metres asl)**					
	200	**400**	**600**	**800**	**1000**	**1200**
Podomyrma ?delbrueckii				░		
Podomyrma sp. G			░	░		▒
Pristomyrmex foveolatus	▒	▓	▒			
Rhopalothrix orbis			░			
Solenopsis	▓	▓	█	█	▓	█
Strumigenys deuteras	░	▒	▒	▓	▒	▓
Strumigenys emdeni				▒	▒	
Strumigenys guttulata	▒					
Strumigenys near *perplexa*		▒	▒			
Strumigenys varanga				░		
Strumigenys zygon		▒	▒			
Syllophopsis sp. A			░			
PONERINAE						
Anochetus graeffei		░				
Cryptopone rotundiceps					░	▓
Hypoponera sp. A	█	█	█	█	█	▓
Hypoponera sp. B			▒	█	█	
Hypoponera sp. C	▓	▓	▓	▓		
Hypoponera sp. E			░			
Leptogenys bidentata	▒	░	▒		░	▒
Leptogenys nr *mjobergi*				░	▒	
Leptogenys turneri	░				▒	
Mesoponera australis	▓	▓	█	█		
Platythyrea parallela	▒	▒				
Ponera leae				░		
Pseudoneoponera sp. A	░		▒			
Pseudoneoponera sp. B	▒		▒	▒		
PROCERATIINAE						
Discothyrea sp. A				░		
Discothyrea sp. B	░		░		░	░
Discothyrea sp. C				░		
Proceratium australe	░				░	
PSEUDOMYRMECINAE						
Tetraponera punctulata			░			

FIGURE 1. Overall number of ant species collected from each band of elevation at Eungella (bars) and at Lamington (points), showing broad patterns of species richness across elevation. Richness values between transects are not directly comparable due to differing sampling intensity (see Burwell & Nakamura, 2011, for details of sampling protocol at Lamington). At Eungella, sampling intensity varied among elevational bands both in terms of the number of unique sites (four at 200 m and 1200 m, five at 1000 m, and seven at 400, 600 and 800 m) and the number of samples (eight at 200 and 1200 m, and 13 at 400, 600, 800 and 1000 m).

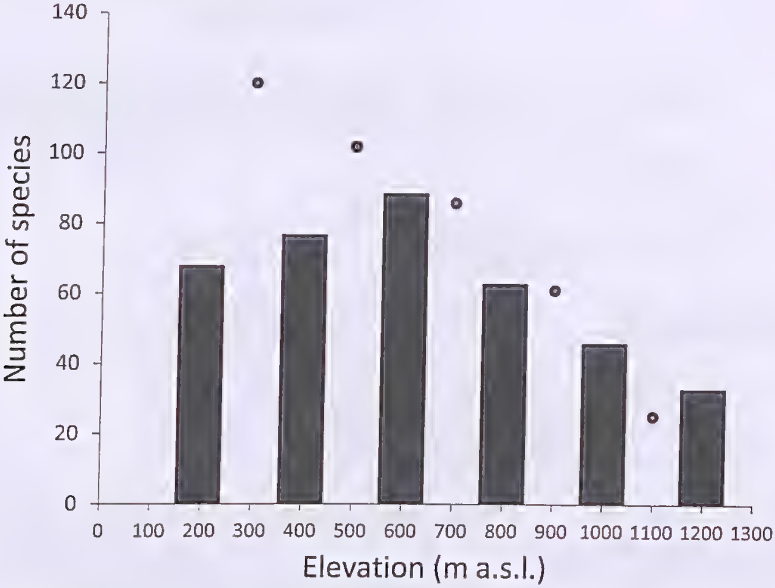

FIGURE 2. NMDS ordination of ant species assemblages from samples collected along a gradient of elevation in the Eungella region. Ordination based on incidence (presence/absence) of species from pooled data from five different sampling methods. Solid oval encloses low-elevation samples from 200 to 600 m asl, and dashed oval encloses high-elevation samples from 800 to 1200 m asl.

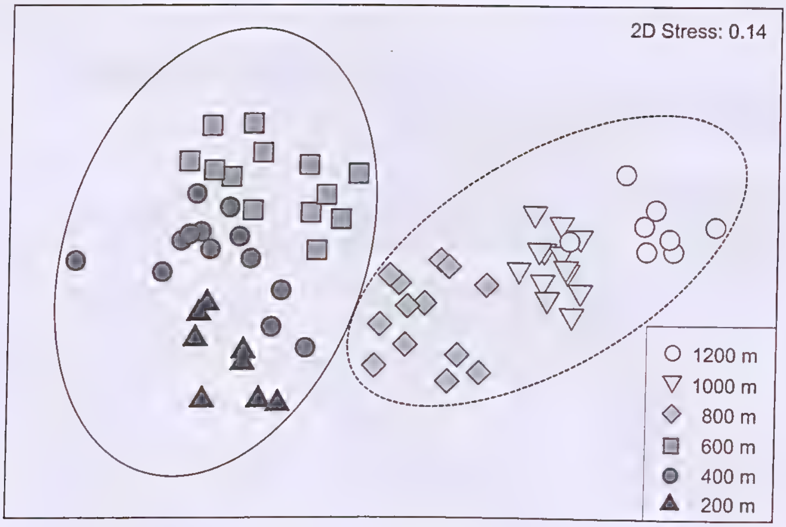

TABLE 3. Subfamily and generic distribution of 142 ant species and the genus *Solenopsis*, recorded from the entire Eungella elevational gradient. Genera marked with an asterisk contained at least one species considered to be characteristic of more open forest habitats. NA – not applicable, as specimens of *Solenopsis* were not sorted to morphospecies.

Genus	# spp.
AMBLYOPONINAE	
Amblyopone	2
Onychomyrmex	4
Prionopelta	1
DOLICHODERINAE	
Anonychomyrma	5
Iridomyrmex	1
Leptomyrmex	2
*Ochetellus**	1
Tapinoma	3
Technomyrmex	1
Turneria	1
DORYLINAE	
Lioponera	1
Zasphinctus	3
ECTATOMMINAE	
Rhytidoponera	5
FORMICINAE	
Acropyga	2
Camponotus	4
Colobopsis	3
Echinopla	1
Myrmecorhynchus	1
Notoncus	1
Notostigma	1
Nylanderia	1
FORMICINAE (*cont.*)	
Oecophylla	1
*Opisthopsis**	1
Paraparatrechina	2
*Polyrhachis**	10
Prolasius	2
Pseudonotoncus	1
Stigmacros	1
HETEROPONERINAE	
Heteroponera	2
LEPTANILLINAE	
Leptanilla	1
MYRMECIINAE	
Myrmecia	2
MYRMICINAE	
Aphaenogaster	1
Calyptomyrmex	1
*Cardiocondyla**	1
Carebara	3
Colobostruma	3
Crematogaster	5
Eurhopalothrix	1
Lordomyrma	1
Mayriella	3
Meranoplus	1
Monomorium	7
MYRMICINAE (*cont.*)	
Myrmecina	2
Orectognathus	4
Pheidole	7
Podomyrma	7
Pristomyrmex	1
Rhopalothrix	1
Solenopsis	NA
Strumigenys	6
Syllophopsis	1
PONERINAE	
Anochetus	1
Cryptopone	1
Hypoponera	4
Leptogenys	3
Mesoponera	1
Platythyrea	1
Ponera	1
Pseudoneoponera	2
PROCERATIINAE	
Discothyrea	3
Proceratium	1
PSEUDOMYRMECINAE	
Tetraponera	1
TOTAL GENERA	62
TOTAL SPECIES	143

Below we provide an overview of the fauna of each subfamily, highlighting records of interest. We also compare our data with the species recorded along elevational gradients in subtropical rainforest at Lamington National Park (300 to 1100 m asl) in south-eastern Queensland, and tropical rainforest at Mt Lewis (200 to 1200 m asl) in the Wet Tropics bioregion in northern Queensland.

Subfamily Amblyoponinae (3 genera, 7 species)

We recorded two species of *Amblyopone*. *Amblyopone australis* occurred across the entire gradient, becoming more frequently collected as elevation increased; it was recorded from all 1200 m asl sites each time they were surveyed. At Lamington in south-eastern Queensland, the same pattern was observed with *A. australis* occurring across the entire gradient from 300 to 1100 m asl, increasing in frequency with increasing elevation. In contrast, at Eungella *Amblyopone hackeri* was collected infrequently and only from sites at 1000 m asl. This species was originally described from Lamington National Park and is known from south-eastern Queensland and eastern New South Wales as far south as Sydney. There is a previous record of *A. hackeri* from Eungella National Park (Australian National Insect Collection sourced via the ALA). The Eungella population is highly disjunct and appears restricted to the high-elevation subtropical forests.

The litter-inhabiting *Prionopelta robynmae* was recorded infrequently from sites at only 600 m asl. This is a widely distributed species of *Prionopelta* occurring from Papua New Guinea and from eastern coastal Australia as far south as Victoria, with records from the Top End of the Northern Territory (Shattuck, 2008). At Lamington, *P. robynmae* occurred from 300–900 m asl.

Four species of *Onychomyrmex* were infrequently collected from 400 to 1200 m asl. As there has been no recent taxonomic revision of *Onychomyrmex*, none were assigned to described species. *Onychomyrmex* is confined to Australia, with most species distributed along the east coast from Cape York Peninsula to south-eastern Queensland. A single species, *O. glauerti*, recently transferred to *Onychomyrmex* by Ward & Fisher (2016), is also known from south-western Western Australia. Along the east coast, *Onychomyrmex* is essentially tropical, with a single undescribed species known from subtropical, south-eastern Queensland (Lamington National Park, 500 and 900 m asl, CJB unpublished data). We also recorded the south-eastern Queensland species, *Onychomyrmex* QM.1, from Eungella at a single site at 1000 m asl in March 2014. Two of the remaining *Onychomyrmex* species from Eungella were not represented from our Lamington and Mt Lewis gradients, but a very small, pale species, *Onychomyrmex* sp. A, collected once from 200 m asl at Owens Creek, closely resembles a species collected once from Mt Lewis at 400 m asl.

Subfamily Dolichoderinae (7 genera, 14 species)

Dolichoderines were relatively poorly represented in our surveys, with only fourteen species from seven genera: *Anonychomyrma* (5 species), *Tapinoma* (3 spp.), *Leptomyrmex* (2 spp.), and single species each of *Iridomyrmex*, *Ochetellus*, *Technomyrmex* and *Turneria*.

Two of the species of *Anonychomyrma* are of note because they co-occurred on either our Mt Lewis or Lamington gradients. *Anonychomyrma* QM.4 is a relatively large and densely pilose species that may be *Anonychomyrma gilberti*. At Eungella this species was recorded from 200 to 1000 m asl. At lower elevations it was particularly abundant and ubiquitous: it was recorded from all surveys of all sites from 200 to 600 m asl. With increasing elevation it became more spatially and temporally patchy, recorded from 77% and 23% of site surveys at 800 m asl and 1000 m asl, respectively, and was not collected at any 1200 m asl sites. At Mt Lewis in the Wet Tropics this species occurred from 400 to 1200 m asl, but oddly was not recorded from sites at 1000 m asl. This is a largely arboreal species, and differences in the structure of the forest at the upper elevations at Mt Lewis – the canopy at 1000 m was much higher than at 1200 m asl – may explain why we did not sample the species at ground level.

The smaller *Anonychomyrma* QM.3 inhabited higher elevations at 800, 1000 and 1200 m asl, where it was recorded from 46% of surveyed sites at 800 m and all sites at 1000 m and 1200 m. In contrast, at Lamington *Anonychomyrma* QM.3 occurred at much lower elevations and was recorded from all survey sites between 300 and 900 m asl, and half the sites at 1100 m asl. The degree of the downslope extension of its range in the subtropics seems unlikely to be due only to the influence of the higher latitude. It may be that the populations of *Anonychomyrma* QM.3 at Eungella and Lamington are not conspecific but rather different species with differing thermal tolerances. Alternatively, perhaps the ubiquity of *Anonychomyrma* QM.4 at lower elevations on the Eungella gradient displaces *Anonychomyrma* QM.3 upslope.

Three species of *Tapinoma* were recorded from the Eungella gradient, all of which also occurred at Lamington, and one, *Tapinoma* QM.2, that also occurred at Mt Lewis. This species was only recorded from a single site at 600 m asl at Mt Lewis, whereas it occurred over most of the gradient at Eungella and Lamington: 200–1000 m asl and 300–1100 m asl, respectively.

The single species of *Technomyrmex* collected at Eungella, *T. jocosus*, was recorded from the entire elevational gradient (200–1200 m asl). It also occurred at Lamington, but only from 300–700 m asl. *Technomyrmex jocosus* is widely distributed in Australia, occurring along the east coast from the Wet Tropics, Queensland to Tasmania, Victoria and southern South Australia, and extending west to south-western Western Australia (Bolton, 2007). Two species of 'spider ant' were recorded in our surveys, *Leptomyrmex rufipes* (400–800 m asl) and *Leptomyrmex mjobergi* (200–600 m asl), both of which have been previously recorded from the Eungella region (Lucky & Ward, 2010). *Leptomyrmex mjobergi* occurs along the east coast from the northern Wet Tropics south to the Queensland-New South Wales border (Lucky & Ward, 2010) but was not collected at either our Mt Lewis or Lamington gradients. *Leptomyrmex rufipes* has a similar distribution but extends to the base of Cape York Peninsula in the north (Lucky & Ward, 2010). Similarly, *L. rufipes* was not recorded from the Mt Lewis gradient, and only a single specimen was collected from a 200 m asl plot at Lamington.

Turneria bidentata is an arboreal, lignicolous species which, like many formicines with comparable nesting habits, was recorded from lower elevations (200–600 m asl) at Eungella. In Australia, *T. bidentata* is known from the Top End of the Northern Territory and along the east coast from Cape York south to about Taree in northern New South Wales (Shattuck, 1990; records sourced from the ALA). A single species of

Iridomyrmex, *I. calvus*, was recorded from our surveys, from single sites at each of 400 and 600 m asl. *Iridomyrmex calvus* is known from the southern Australian mainland, Tasmania, Lord Howe Island, Norfolk Island and New Caledonia (Heterick & Shattuck, 2011). Specimens of *I. calvus* from Australia were originally described as *I. notialis* (Shattuck, 1993). Our collections represent the northernmost Australian records of the species.

Subfamily Dorylinae (2 genera, 4 species)

Several collections of *Lioponera*, often previously referred to as *Cerapachys* (e.g. Shattuck, 1999), were made across the full elevational gradient (200 to 1200 m asl). Specimens varied somewhat in size, the shape of the postpetiole and the form of the frontal carinae. This variation, however, is difficult to interpret, and we have taken a conservative approach and consider them all conspecific at present. They belong to the *turneri* species group of Brown (1975) which comprises mostly small, predominantly black species inhabiting forests in eastern and south-western Australia, New Guinea and New Caledonia.

Three distinct species of *Zasphinctus*, often previously referred to as *Sphinctomyrmex* (e.g. Shattuck, 1999), were represented among our collections. The large, dark *Zasphinctus turneri* was collected once from pitfall traps at 200 m asl. This species has relatively large eyes and twelve-segmented antennae, and has been recorded from the Wet Tropics south to west of Bundaberg, Queensland. The two other *Zasphinctus* belong to Brown's (1975) *steinheili* species group, consisting of species with 11-segmented antennae and eyeless workers from Australia, New Guinea and New Caledonia. One is probably *Z. steinheili* itself, originally described from specimens from Mackay, and was collected from sites at 600–1200 m asl. The second, which may be *Z. duchaussoyi*, was represented by a single collection of very small, pale-coloured workers from a site at 600 m asl.

Subfamily Ectatomminae (1 genus, 5 species)

Five species of *Rhytidoponera* were recorded in our surveys, three of which have been assigned to described species. Two belong to the *impressa*-group of species revised by Ward (1980): *R. chalybaea* and *R. impressa*. *Rhytidoponera chalybaea* was confined to sites at 1200 and 1000 m asl, and was replaced by *R. impressa* at 800 m asl, the only elevation from which the latter species was recorded. Both showed high site and temporal fidelity, particularly *R. chalybaea*, occurring at most sites and most survey occasions within their elevational ranges. *Rhytidoponera chalybaea* is a common ant of subtropical rainforest in southern Queensland and northern New South Wales (Ward, 1980). At our Lamington gradient in south-eastern Queensland, it was common and confined to sites at 300, 500 and 700 m asl, occurring at lower elevations at the higher latitude. Given that *R. chalybaea* was common as low as 300 m asl at Lamington, it might be expected to occur at lower elevations than those recorded at Eungella. However, species interactions may explain this anomaly, given that it was replaced by the closely related *R. impressa* at 800 m asl at Eungella.

In contrast, the elevational range of *Rhytidoponera victoriae*, a member of the *metallica*-group of species, did not differ substantially between the Eungella and Lamington gradients. It was recorded from the majority of sites at 200, 400 and 600 m asl at Eungella, and at Lamington it was recorded from 300 and 700 m asl. At Mt Lewis, however, the elevational range of *R. victoriae* did appear to shift upslope, occurring from 600 to 1000 m asl. The remaining *Rhytidoponera* species from Eungella, *Rhytidoponera* QM.12 (200–600 m asl) and *Rhytidoponera* QM.14 (400–800 m asl), were not recorded from either our Lamington or Mt Lewis gradients.

Subfamily Formicinae (15 genera, 32 species)

This was the second most diverse subfamily represented in our Eungella collections, both in terms of genera and species. The most speciose genera were *Polyrhachis* (10 species), *Camponotus* (4 spp.) and *Colobopsis* (3 spp.), with all other genera represented by one or two species.

Two described species of *Acropyga* were recorded: *Acropyga acutiventris* from two adjacent sites at 600 m asl, and *Acropyga pallida* from a single collection from a site at 800 m asl. Species of *Acropyga* are subterranean ants that live in obligate symbiotic associations with root mealybugs (Pseudococcidae) (Blaimer *et al.*, 2016), although one Australian species has been found associated with a species of Orthezidae (LaPolla *et al.*, 2008). *Acropyga acutiventris* is a tropical species that is widespread in the Oriental, Indo-Australian and Australasian regions (LaPolla, 2004). In Australia, it has been recorded from the Top End of the Northern Territory, and in Queensland from Cape York Peninsula south to Eungella (Taylor, 1992; LaPolla, 2004). *Acropyga pallida* occurs from Australia north to the Philippines and west to Borneo

(La Polla, 2004). It is widespread in Australia, with records from northern Western Australia, the Top End of the Northern Territory, and along the east coast from Cape York Peninsula south to Victoria (Lapolla, 2004). Our collection appears to be the first record of the species from the Eungella region. The third Australian species in the genus, *Acropyga myops*, has also been recorded from the Eungella region, but from dry sclerophyll forest (LaPolla, 2004).

A single species of the endemic Australian genus *Myrmecorhynchus*, *M. emeryi*, was recorded from our surveys. *Myrmecorhynchus* is confined to southern and eastern Australia, with three described species with largely arboreal workers (Shattuck, 2015). *Myrmecorhynchus emeryi* is the most widespread, occurring across the southern mainland from south-western Western Australia to southern South Australia, Victoria, eastern New South Wales and south-eastern Queensland (Shattuck, 2015). In addition to our collections, Shattuck (2015) listed specimens from Eungella, which is the northernmost extent of the range of the species. At Eungella, *Myrmecorhynchus emeryi* occurred at sites from 600 to 1200 m asl, and became increasingly common as elevation increased: it was ubiquitous at sites at 1000 and 1200 m asl. At subtropical Lamington, the elevational range of *M. emeryi* was slightly lower, where it was ubiquitous at sites from 500 to 900 m asl but was not recorded from any sites at 1100 m asl.

Two species of *Prolasius* were recorded from the Eungella gradient which have different distribution patterns. One, *Prolasius formicoides*, originally described from Mackay, occurred from as low as 400 m asl to the highest elevations at 1200 m asl. *Prolasius formicoides* is very closely allied, and may well by synonymous with *Prolasius mjoebergella* (Taylor, 1992) originally described from Malanda in the Wet Tropics. *P. mjoebergella* is widespread in the Wet Tropics, and on our Mt Lewis transect occurred from 800 and 1200 m asl, suggesting an upslope shift of its elevational range at lower latitudes if it is indeed synonymous with *P. formicoides*. The other species recorded from Eungella, *Prolasius convexus*, has a more southerly distribution and was originally described from Dorrigo in northern New South Wales. This arboreal species occurred at our south-eastern Lamington gradient from 500 to 900 m asl (Burwell & Nakamura, 2011), whereas at Eungella it was recorded only from 1000 m asl from all five survey sites.

Notostigma carazzii, one of the two species of this Australian endemic genus, is widespread throughout the Wet Tropics bioregion, occurring as far south as Mt Elliot south of Townsville (Taylor, 1992; additional records sourced via the ALA). This species is also known from the Eungella region (Taylor, 1992), the southernmost extent of its range, where we recorded it from sites at 600 to 800 m asl.

Formicine species that nest arboreally were more diverse at lower elevations, 200–600 m asl, of the Eungella gradient, and included both lignicolous and weaving species. Weavers included two species of the subgenus *Cyrtomyrma* of the genus *Polyrhachis* (*Polyrhachis pilosa* and *Polyrhachis mackayi*) and the green tree ant *Oecophylla smaragdina*. Aboreal, lignicolous species, that is, those nesting in hollows in twigs and branches, included *Echinopla turneri*, several species of *Polyrhachis* in the subgenera *Campomyrma* and *Hedomyrma*, and a number of *Colobopsis* species. It should be noted that *Campomyrma* as currently applied appears polyphyletic, with the Australian species forming a clade distinct from the 'true' *Campomyrma* species from Southeast Asia (Mezger & Moreau, 2016). Many of these arboreal nesters from Eungella are largely tropical species. In Australia, *Colobopsis vitrea*, for example, occurs in the Top End of the Northern Territory and in north-eastern Queensland from Cape York south to Mackay (McArthur & Shattuck, 2001). Records of the species from south-eastern Queensland (Mt Coot-tha, Brisbane, Goodna) listed by McArthur & Shattuck (2001) are almost certainly erroneous. Similarly, *Oecophylla smaragdina* is widespread in northern Australia, and extends throughout the tropical east coast of Queensland, extending as far south as Rockhampton and Gladstone in the subtropics (Wetterer, 2017). *Polyrhachis (Hedomyrma) argentosa* shows a similar distribution pattern, occurring from south of Cooktown to the Rundle Range near Gladstone (Kohout, 2000). *Echinopla turneri* has a more restricted distribution, occurring from the Paluma Range in the southern Wet Tropics bioregion south to Yeppoon (Kohout, 2000). Not all lignicolous formicines were confined to the lowlands, with a species of *Colobopsis* and *Polyrhachis (Campomyrma)* collected from sites at 1000 and 1200 m asl.

We recorded a single species of the largely southern Australian genus *Stigmacros*, *Stigmacros major*, along the Eungella gradient. Originally described from Lamington National Park, *S. major* was also collected from our Lamington gradient (Burwell & Nakamura, 2011). Despite the latitudinal difference in the location of the gradients, *S. major* occurred at similar elevations at both Lamington (300–700 m asl) and Eungella (400–600 m asl).

Subfamily Heteroponerinae (1 genus, 2 species)

What we tentatively identified as a single species of *Heteroponera* in the *H. imbellis* species group (*sensu* Taylor, 2011) was recorded from across the entire Eungella elevational gradient. This species-group is known from Iron Range on Cape York Peninsula and from around Cooktown, Queensland, south to southern New South Wales and Victoria, extending west to southern South Australia and south-western Western Australia. Taylor (2011) estimated the group to be represented by six species in collections. The second species of *Heteroponera* recorded in our surveys, *H. crozieri*, is a member of the *leae* species group. This species has previously been recorded from Eungella and occurs from the Clarke Range south to south-eastern Queensland and north-eastern New South Wales (Taylor, 2011). No species of the *relicta* species group, which is confined to the Wet Tropics bioregion (Taylor, 2015), were collected at Eungella.

Subfamily Leptanillinae (1 genus, 1 species)

The subfamily Leptanillinae is represented in Australia by the single widespread species *Leptanilla swani* which also occurs in New Guinea. Although widespread, most records of the species are of alate males, and the subterranean workers are very rarely collected. Two collections of *Leptanilla* workers and associated larvae were made during the Eungella survey, one from 600 m asl and a second from 800 m asl, and are assumed to be *L. swani* based on Baroni Urbani's worker-based key and comparison with images of the types of *L. swani* available on ANTWEB.

Subfamily Mymeciinae (1 genus, 2 species)

Two species of *Myrmecia* were recorded during our surveys. *Myrmecia nigrocincta* was primarily a lowland species, recorded from sites at 200 and 400 m asl with a single collection at 600 m asl. This is a widespread species occurring in eastern Australia from the Wet Tropics in Queensland south to Victoria (Ogata & Taylor, 1991). Specimens of a second large species of *Myrmecia* in the *gulosa* group (*sensu* Ogata & Taylor, 1991) were collected only at high-elevation sites at 1000 and 1200 m asl. Ogata & Taylor (1991) described two new, apparently endemic species of large *Myrmecia* from high elevations at Eungella, *M. eungellensis* and *M. fabricii*. The two species were very similar in appearance, and distinguished by the dimensions of the petiole and the form of the occipital carina and hairs on the body (Ogata & Taylor, 1991). Worker specimens from our collections were examined by R. W. Taylor who concluded that they were *M. eungellensis*. Our specimens show greater than expected variation in the dimensions of the petiole, but all have a complete occipital carina which distinguishes them from *M. fabricii* workers which have the carina interrupted medially. However, given the degree of variability in our specimens, there is a possibility that *M. eungellensis* and *M. fabricii* are synonymous (R. W. Taylor, *pers. comm.*).

Subfamily Myrmicinae (20 genera, 57 species)

By far the most diverse subfamily among our Eungella collections was the Myrmicinae with an estimated 57 species from 21 genera. The most speciose genera along the gradient were *Monomorium* (7 spp.), *Pheidole* (7 spp.), *Podomyrma* (7 spp.), *Strumigenys* (6 spp.), *Crematogaster* (5 spp.) and *Orectognathus* (4 spp.).

Calyptomyrmex is a rarely collected genus of cryptic, litter-inhabiting ants which, in Australia, is confined to tropical and subtropical Queensland and New South Wales (Shattuck, 2011). *Calyptomyrmex fragarus* was a lowland species, recorded from litter extracts from the majority of sites at 400 and 600 m asl, and a single site at 200 m asl. This species is known from the Bluewater and Paluma Ranges in the southern Wet Tropics, with a single previous record from Finch Hatton Gorge in the Eungella region (Shattuck, 2011). *Pristomyrmex foveolatus* was also only recorded from the lowlands (200–600 m asl), largely from litter extracts. This rainforest-inhabiting species has been recorded throughout the Wet Tropics and from a number of localities in the Central Queensland Coast: Mt Dryander, the Conway Range, and Finch Hatton Gorge in the Eungella region (Taylor, 1965; Wang, 2003). Other myrmicine genera with species largely collected from litter extracts included *Strumigenys* (6 spp.), *Carebara* (3 spp.), *Mayriella* (3 spp.), with *Lordomyrma*, *Eurhopalothrix* and *Rhopalothrix* all represented by single species.

Four species of the trap-jaw, dacetine genus *Orectognathus* were recorded along the Eungella gradient. *Orectognathus parvispinus* was originally described from Eungella (Taylor, 1977) and may be endemic to the region. The type series was collected from 780 m asl (Taylor, 1977), and we recorded it from sites at 800, 600 and 400 m asl. Two of the *Orectognathus* species also occurred at our Lamington gradient. *Orectognathus mjobergi* occurs along the eastern Australian coast from the Wet Tropics to central New South Wales

(Taylor, 1977). We recorded it only from 600 m asl at Eungella, whereas at Lamington it was collected only at 300 m asl. *Orectognathus versicolor* is known from coastal New South Wales north to south-eastern Queensland, with a disjunct population in the Eungella region (Taylor, 1977). At Lamington, *O. versicolor* occurred at most survey sites from 300 to 900 m asl, whereas at Eungella it was sampled only from higher elevations between 800 and 1200 m asl. The remaining *Orectognathus* was collected from single sites at both 600 and 800 m asl, and is an undescribed species close to *O. coccinatus*.

A number of species of *Monomorium* were collected along the gradient. Two species are of interest because they were also collected along our Lamington transect in south-eastern Queensland. One of these keys to *Monomorium kiliani* using Heterick's (2001) key to Australian species of *Monomorium*. According to Heterick (2001), *M. kiliani* is widespread in southern Australia, occurring from southern South Australia, Victoria, Tasmania and New South Wales. Records of *M. kiliani* from Western Australia are questionable (B. Heterick, *pers. comm.*). At Eungella, *M. kiliani* was collected only once in pitfalls at a 1200 m asl site in March 2014; this collection represents a substantial northern extension of the known range of the species. At our Lamington gradient, this species was recorded from sites at 500, 700 and 1200 m asl. At Lamington, it appeared to be more active in cooler seasons. In surveys conducted in the austral summer, early autumn and mid-spring (January, February, March and October), *M. kiliani* was detected in low numbers only at the highest elevations of the Lamington gradient (1100 m asl). In mid-winter, however, the abundance of *M. kiliani* in litter extracts from 1100 m asl increased substantially, and it was detected in samples from one site at 700 m asl and three sites at 500 m asl. The second *Monomorium* species of interest keys to *M. leae* (which may well be a complex of species, B. Heterick, *pers. comm.*) using Heterick's (2001) key. It appeared to show an upslope shift in at least its lower elevational range at Eungella compared with Lamington, recorded from 300–1100 m asl at Lamington and 800–1200 m asl at Eungella.

Species of *Myrmecina* are small, cryptic ants most commonly collected from leaf litter extracts. The Australian fauna consists of 13 described species which are mostly found in north-eastern Australia (Shattuck, 2009). We recorded two species from the Eungella gradient: *Myrmecina difficulta* from 600–1200 m asl, and *Myrmecina inaequala* from 200–800 m asl.

Seven species of *Pheidole* were collected along the gradient but, in the absence of recent revisionary work on the Australian species, we have not attempted to assign them to described species nor matched them across the three elevational gradients. The exception was *Pheidole dispar*, which was previously included in the monotypic genus *Machomyrma* (see Shattuck, 1999) which has recently been synonymised with *Pheidole* (Ward *et al.*, 2015). Within the Eungella transect, a number of *Pheidole* species appear good candidates for future monitoring of elevational range shifts due to warming temperatures. The genus includes species apparently confined to lower elevations (300–600 m asl – *Pheidole* sp. B and *Pheidole* sp. F) and another, *Pheidole* sp. E, confined to high elevations (1000–1200 m asl). These species also show quite high site and survey fidelity within their elevational ranges, increasing their suitability as indicator species.

The majority of Australian species within the myrmicine genera *Crematogaster* and *Podomyrma* are arboreal species generally nesting within hollows in twigs and branches, particularly in rainforest habitats. Both were well represented along the Eungella gradient, with the majority of species recorded from lower elevations between 200 and 600 m asl. However, this pattern should be treated with caution with regards to the *Podomyrma* species, given they were collected uncommonly and a number were recorded from higher elevations. The Australian fauna of both genera is in need of revision, and identification of the *Podomyrma* species was facilitated by an unpublished key to described species and species-groups supplied by R. W. Taylor.

Subfamily Ponerinae (8 genera, 14 species)

The subfamily Ponerinae was represented by at least 14 species in 8 genera. *Hypoponera* (at least four species), *Leptogenys* (3 spp.) and *Pseudoneoponera* (2 spp.) were the only genera with multiple species. *Anochetus*, *Cryptopone*, *Mesoponera*, *Ponera* and *Platythyrea* were all represented by single species.

Hypoponera is a taxonomically challenging genus, and we have only tentatively assigned specimens of the genus to morphospecies. As such, we did not identify any as described species, nor have we matched morphospecies across the Eungella, Lamington and Mt Lewis gradients. Three of the four Eungella morphospecies were largely ground-inhabiting, collected mainly in litter extracts, but one was usually collected under the rotten bark of fallen logs.

Among the species of *Leptogenys*, the small *Leptogenys bidentata*, originally described from Mackay, occurred along the entire length of the Eungella gradient (200–1200 m asl). *Leptogenys turneri*, a much larger species with a posterodorsal spine projecting from the petiolar node, was recorded from a single site at 200 m asl, and two sites at 1000 m asl. *Leptogenys turneri* was also originally described from Mackay and has been previously recorded from Eungella and the Paluma Range in the southern Wet Tropics bioregion (Taylor, 1988). According to Taylor (1988), the closely related *Leptogenys longensis*, which also possesses a spinose petiolar node, replaces *L. turneri* further north in the Wet Tropics from Koobooloomba in the Atherton Uplands north to Cape Tribulation. The third *Leptogenys* species recorded in our surveys (800 and 1000 m asl) is close to *L. mjobergi* collected from our Lamington transect, but appears to be a distinct species. *Leptogenys excisa* is known from rainforests in the Eungella region (Taylor, 1988) but was not recorded on our surveys.

Two of the remaining ponerines, *Cryptopone rotundiceps* and *Mesoponera australis*, occurred across all three gradients. *Cryptopone rotundiceps* is usually found nesting in rotten, fallen logs, and its recorded elevational ranges across the three gradients were not consistent with the expectation of upslope range shifts associated with decreasing latitude. At Lamington, *C. rotundiceps* occurred from 500 to 1100 m asl (Burwell & Nakamura, 2011, as *Cryptopone* IBISCA.1), at Eungella only from 1000–1200 m asl, and at Mt Lewis (based on a single survey) from 600–1200 m asl. Similarly, the elevational ranges of the ground-nesting *Mesoponera australis* were difficult to interpret, as the ant only occurred at 300 m asl at Lamington (Burwell & Nakamura 2011, as *Pachycondyla australis*), and from 200 to 800 m asl at Eungella. At Mt Lewis it was collected only twice, once at 400 m asl and once from 1000 m asl.

Proceratiinae (2 genera, 4 species)

Three unidentified species of *Discothyea* and a single species of *Proceratium* were recorded from Eungella. The species of both genera are minute, litter-inhabiting ants, and the majority of our collections were from litter extracts. We also collected species of *Discothyrea* from our Lamington and Mt Lewis gradients but did not match them across the gradients as the specimens were unavailable. Single specimens of *Proceratium australe* were collected from each of our three Eungella surveys, one each from 200, 800 and 1000 m asl. *Proceratium australe* is a morphologically variable species occurring along the eastern Australian coast from the Wet Tropics region in Queensland to southern New South Wales, and has previously been recorded from the Eungella region (Baroni Urbani & Andrade, 2003).

Pseudomyrmecinae (1 genus, 1 species)

A single specimen of *Tetraponera punctulata* was collected from a Malaise trap at one of the 600 m asl sites. *Tetraponera punctulata* is the most widespread Australian species of the genus, occurring across most of the continent except the extreme south and parts of the arid interior (Ward, 2001). It mostly inhabits woodlands and open forests, but has been collected in rainforest in Queensland and Papua New Guinea (Ward, 2001). Species of *Tetraponera* are lignicolous, nesting arboreally in hollows in twigs and branches (Ward, 2001).

General Discussion

In total we collected at least 142 species of ants across the Eungella elevational gradient of 200 to 1200 m asl, which comprised a total of 34 sites each sampled between one and three times. Here we compare the total species pools recorded on our Lamington (20 sites from 300–1100 m asl) and Mt Lewis gradients (20 sites from 400–1200 m asl), but quantitative analysis is difficult due to the variation in sampling intensities and the extent of the elevational gradients. Sampling intensity at our Wet Tropics gradient (a single survey) was too low for meaningful comparison with the two more southerly gradients. Sampling intensity at the Lamington gradient was at least comparable, where a similar total of 145 ant species was recorded using the same sampling methods on three separate surveys (143 species noted in Burwell & Nakamura, 2011, but more careful sorting yielded additional species). As ant species richness typically declines with increasing latitude (Dunn *et al*., 2009), the more tropical Eungella gradient would be expected to be more diverse, but our results suggest that the more southerly Lamington gradient may have a larger species pool. However, when comparisons were made on the basis of a single survey in the same season, species richness declined with increasing latitude from Mt Lewis to Eungella to Lamington (Burwell & Nakamura, 2016), although, as noted above, the Eungella gradient spanned a greater range of elevations with more sites.

Comparing the total numbers of species collected at sites within each band of elevation along the gradient, species richness peaked at 600 m asl at Eungella, with monotonic declines in species richness with increasing and decreasing elevation (Figure 1) from 600 m. In contrast, at Lamington, species richness peaked at the lowest elevation and monotonically declined with increasing elevation (Figure 1; and see Burwell & Nakamura, 2011). Comparisons of total species richness at each elevation at Eungella (and Lamington) are also confounded by unequal numbers of sites sampled differing numbers of times, with more sites and total site surveys particularly at 400, 600 and 800 m asl (Table 1). When correcting for sampling intensity across the two gradients, Burwell & Nakamura (2016) found broadly similar patterns, richness peaking at mid-elevations at Eungella and at the lowest elevations at Lamington. They suggested that the lower richness at lower elevations at Eungella may be due to historical lowland biotic attrition (Burwell & Nakamura, 2016).

We found progressive turnover in ant species composition with increasing elevation at Eungella. There appeared to be, however, two different gradients of turnover in the ant fauna, one from 200 to 600 m asl and the other from 800 to 1200 m asl. Assemblages of moth species sampled with light traps along the same elevational gradient were similarly divided into lowland and upland assemblages, as were assemblages of tree species (Odell *et al*., 2016). Tree species composition is likely to strongly influence the species composition of herbivorous Lepidoptera; however, it is unlikely to drive ant assemblages to the same extent. Nowrouzi *et al*. (2016) found similar patterns of compositional disjunction between 600 and 800 m asl in a number of subregions within the Australian Wet Tropics, including the Carbine Uplands where our Mt Lewis gradient is located. This zone of disjunction coincided with a strong environmental threshold of seasonal stability in moisture associated with cloud 'stripping' (Nowrouzi *et al*., 2016). Given that the upland rainforests of the Eungella plateau are a northern outlier of subtropical rainforest (Weber *et al*., 2013), long-term climate stability may well underlie the difference in the ant fauna of the uplands in Eungella, as suggested for the Wet Tropics by Nowrouzi *et al*. (2016).

A number of factors may drive the apparent differences in composition between the ant faunas of the lowlands and highlands at Eungella: greater numbers of tropical species in the lowlands and, conversely, greater numbers of subtropical species in the highlands; and a greater representation of arboreal-nesting species in the lowlands compared with the highlands. Many primarily tropical ant species were collected only from sites from 200 to 600 m asl at Eungella, and likely contributed to differences between the lowland and upland ant faunas of the region. Some ground- and litter-inhabiting species demonstrated this distribution pattern including, for example, *Zasphinctus turneri* (Dorylinae), *Acropyga acutiventris* (Formicinae) and *Strumigenys guttulata*, *Pristomyrmex foveolatus* and *Calyptomyrmex fragarus* (Myrmicinae) (Table 2). In particular, in the lowlands, there was a substantially greater representation of species nesting and foraging arboreally, compared with the highlands. This was the case for multiple genera and subfamilies: for example, *Tapinoma* and *Turneria* (Dolichoderinae); *Colobopsis*, *Echinopla*, *Oecophylla*, and the *Polyrhachis* subgenera *Campomyrma* and *Hedomyrma* (Formicinae); *Crematogaster* and *Podomyrma* (Myrmicinae); and *Platythyrea* (Ponerinae).

The higher elevations at Eungella, and in particular the rainforests at 1000 and 1200 m asl, featured a number of subtropical species that also occurred at our Lamington gradient. In many cases, but not all, Eungella represents the northernmost extent of their known geographic ranges. A number of subfamilies contained taxa fitting this distributional pattern. Notable examples included: *Amblyopone hackeri* (Amblyoponinae); *Anonychomyrma* QM.3 (Dolichoderinae); *Rhytidoponera chalybaea* (Ectatomminae); *Myrmecorhynchus emeryi* and *Prolasius convexus* (Formicinae); *Monomorium 'leae'* and *Monomorium kiliani* (Myrmicinae). Also recorded only from 1000 and 1200 m asl in our surveys were two species, *Myrmecia eungellensis* and an undescribed species of *Notoncus*, that appear to be endemic to the Eungella region, or at least the Clarke Range. A second species of *Myrmecia*, *M. fabricii*, may also be restricted to the high elevations of the Eungella region, but there are some questions regarding its validity as a species distinct from *M. eungellensis*. *Orectognathus parvispinus* is also currently known only from the Eungella region, but occurs at somewhat lower elevations, 400–800 m asl.

Comparing the observed elevational ranges of species that occurred at both the Eungella (21.1°S) and Lamington (28.1°S) gradients, we found inconsistent responses to the approximately 7° difference in latitude between the gradients. However, as would be predicted, at least some species had higher elevational ranges at Eungella than at Lamington. Species that showed relatively high site and temporal fidelity across both gradients provided the more convincing examples, which involved upslope shifts of both lower and/or upper range margins at Eungella. Examples of lower range margin shifts included *Monomorium 'leae'* (300–1100 m at Lamington versus 800–1200 m at Eungella) and *Anonychomyrma* QM.3 (300–1100 m at Lamington versus 800–1200 m at Eungella), whereas *Myrmecorhynchus emeryi* appeared to show a shift in its upper range margin (500–900 m at Lamington versus 600–1200 m at Eungella). The upper and lower range margins of *Orectognathus versicolor* differed between transects (300–900 m at Lamington versus 800–1200 m at Eungella). *Rhytidoponera chalybaea* showed a similar pattern, occurring at 300–700 m at Lamington versus 1000–1200 m at Eungella. At Eungella, the potential influence of the closely related *R. impressa* on the lower range margin of *R. chalybaea* is worthy of attention, given that *R. impressa* replaced *R. chalybaea* at 800 m asl. With the exception of *R. chalybaea*, many of the species listed above seem to track their climatic envelopes and are not strongly influenced by other factors such as competition and other habitat conditions. These species are potentially a good predictor set of species to quantify the impacts of future climate change.

In conclusion, the ant fauna of the Eungella region appears to be an amalgam of different faunal elements. Rainforest ants from the lowlands include a greater representation of tropical elements, including a number of species whose distributional ranges extend only as far south as the Clarke Range. In addition, a greater number of arboreal-nesting species, including weavers and lignicolous species, are found in the lowlands. The ant fauna of the upland rainforest has a greater representation of largely subtropical ant species, many of which do not occur farther north than the Clarke Range. At least some ant species, two species of *Myrmecia*, *Orectognathus parvispinus* and an undescribed species of *Notoncus*, appear to be restricted to the Eungella region, or at least the wider Clarke Range. The ant fauna of our Eungella elevational gradient represents an ecotone of tropical and subtropical elements. The distributional patterns of ants at Eungella clearly demonstrate that this area is highly significant in terms of conservation. The baseline information presented here, in combination with ongoing monitoring, will be useful in quantifying the ecological impacts of future climatic change.

ACKNOWLEDGEMENTS

Eungella fieldwork undertaken in March 2013 was supported by the Queensland-Chinese Academy of Sciences Biotechnology Fund (GJHZ1130), Griffith University, the CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden (XTBG), Chinese Academy of Sciences, the Queensland Museum and Queensland Herbarium. Fieldwork undertaken in November 2013 and March 2014, part of the Eungella Biodiversity Survey, was funded by Griffith University and the Mackay Regional Council, and led by Roger Kitching and Louise Ashton. We thank our colleagues who assisted with the collection of ant samples in the field, but in particular Elliot Leach, Narumi Kimura, Claire Gely and Jess Mackie. Thanks also to Karin Koch and Susan Wright for their assistance in specimen curation. We also thank Jonathan Majer and Brian Heterick for the helpful comments on an earlier draft of the manuscript.

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THE PYRALOIDEA OF EUNGELLA: A MOTH FAUNA IN ITS ELEVATIONAL AND DISTRIBUTIONAL CONTEXT

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An intensive, two-season survey of moths along an elevational transect from 200 to 1200 m above sea level was an integral part of the recent Eungella biodiversity survey. The overall results have been published elsewhere. In this paper we examine in finer detail the patterns of distribution and faunistics of one of the dominant taxa from that dataset. The Pyraloidea comprise two families of so-called micro-moths, the Pyralidae and the Crambidae. Overall we sampled more than 7000 individuals of more than 100 species. In spring these were principally in the lowland sites, but the summer samples were more evenly spread across elevations. In both seasons characteristic upland and lowland assemblages were apparent, separating at about 700 m above sea level. These elevational patterns were driven statistically by a small group of abundant species. Focusing on the Pyraustinae-Spilomelinae clade (91 species in our samples) and comparing them with samples from other Australian rainforest locations suggests that the Eungella forests represent the southernmost limits for 24 species, and the northern limits for five species. In other cases, the species is known from sites both north and south of Eungella.

Keywords: Pyraloidea, Spilomelinae/Pyraustinae, Eungella, elevation, distribution

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INTRODUCTION

The Lepidoptera, the butterflies and moths, are predominantly herbivorous and, within all 'green' ecosystems, play an important role in connecting the primary producing plants to the superimposed animal food-web, principally through the consuming activities of their larvae. Estimates vary, but there may be close to a million species within the Order, most of which are night-flying moths. As a group, the moths are ideal for comparative studies that aim to examine changes in community structure across ecological gradients such as latitude or elevation. The moths are highly speciose in most locations; are readily sampled using light traps; and are relatively well known taxonomically (although large gaps in our knowledge remain).

For all of these reasons, they were one of the focal groups targeted in the recent Eungella biodiversity survey (Ashton *et al*., this volume). Specifically, we sampled all moths with a forewing length of 1 cm or more, plus additional smaller members of selected families (including the Crambidae and Pyralidae). An analysis of the results for this entire fauna has been presented by Odell *et al*. (2016). These authors found a clear demarcation between moth assemblages at 800 m above sea level and higher, compared with those at lower elevations (see 'Methods' below) for both spring (November) and late summer (March) samples. The samples collected over two seasons were dominated by four groups of species within the Order – the families Erebidae, Geometridae and Noctuidae, together with the superfamily Pyraloidea. Together, these four taxa (comprising five families) made up 65% of the spring samples and 76% of the late summer catches. In each case the Pyraloidea, *viz*. the families Crambidae and Pyralidae, were was the most abundant taxon in both seasons (26% of all moths collected in spring, 35% in late summer) (Figures calculated from Odell *et al*.'s (2016) Table 2).

The Odell *et al*. (2016) analysis further nominated 'indicator species' based on an IndVal analysis (Dufrene & Legendre, 1997) which identifies species that are both restricted to and occur consistently within particular elevational bands. Of particular interest in the present context was the identification of nine species of Pyraloidea among the 23 species' 'predictor set' (*sensu* Kitching & Ashton, 2013) across the two seasons sampled.

For these reasons as well as their intrinsic ecological interest, we have chosen to analyse the catches of Pyraloidea (Pyralidae and Crambidae) in more detail in this paper. We further compare the species distributions of two of the major subfamilies within the Crambidae (Pyraustinae and Spilomelinae) against similar samples collected by us over seven other north-eastern Australian rainforest localities.

The Pyraloidea represent one of the largest groups within the Lepidoptera. Globally, many species remain undescribed and many of the larger genera are in need of revision. Nevertheless, Munroe & Solis (1999) estimated that there were 16,000 described species and at least as many awaiting attention. These authors also confirmed the two subsumed taxa, the Pyralidae and the Crambidae, as full families (following Minet, 1982).

In Australia, and based on the most recent checklists (Neilsen, Edwards & Rangsi, 1996; https://biodiversity.org.au/afd/mainchecklist), the described species within the superfamily represent somewhat more than 1200 species (ca 480 of Pyralidae and ca 770 of Crambidae. This establishes the Pyraloidea as one of the more speciose superfamilies in the Australian lepidopterous fauna. Conventionally designated by collectors as 'micro'-moths, the pyraloids in general are relatively large as adults (at least compared with other 'micros' – although some minute forms are placed within the superfamily). The taxon contains some species of considerable economic importance, including the notorious wax-moth (*Galleria mellonella*), a pest of beehives; the flour moth (*Pyralis farinalis*), a pest of stored grain; as well as a wide range of forest and crop pests (lists in Common, 1990; Neilsen *et al*., 1996).

In a recent multi-locus DNA-based phylogeny of the superfamily, Regier *et al*. (2012) provided evidence for five subfamilies within the Pyralidae (*s.s.*) and twelve putatively monophyletic subfamilies within the Crambidae. Within the Crambidae, their placing of the Schoenobiinae suggests this subfamily is paraphyletic, associated with the Acentrotinae. Their analyses did not include material from the Cymbalomiinae. In the present context they identified the two subfamilies, the Pyraustinae and the Spilomelinae (designated as the single subfamily Pyraustinae (*s.l.*) by Common (1990) and other earlier authors), as forming a clear isolated clade which they refer to as the 'PS clade', which also contains the previously recognised, aberrant subfamily, the Wurthiinae. This clade is sister to all the other Crambidae. This is significant here because we have chosen this clade, by far the most speciose within the superfamily, for more detailed analysis (see below).

In this treatment, then, we address four interrelated questions.

- Do members of the Pyraloidea from the Eungella rainforests form elevation-specific assemblages and, if so, do these reflect the patterns shown by the moth fauna as a whole?
- Are there seasonal differences in elevational patterns shown by the Pyraloidea?
- If there is elevational partitioning, which species are best correlated with the observed patterns?
- How widespread beyond Eungella are members of the dominant subfamilies Pyraustinae and Spilomelinae (the 'PS clade') which were encountered?

METHODS

The Eungella Biodiversity Survey

Details of the study sites and sampling methods have already been presented by Odell *et al*. (2016), and further detail is provided in companion papers (Ashton *et al*., this volume). Accordingly, summaries only are provided here. The two aforementioned works also contain maps of the sampling sites.

Eungella National Park

All study sites were located within the rainforest sections of Eungella National Park (21°S, 148°E) and Pelion State Forest located on the Clarke Range some 80 km west of Mackay in central Queensland. Four study plots were established within each of six elevational bands – at 200 m, 400 m, 600 m, 800 m, 1000 m and 1200 m above sea level. In each case, the elevations of plots fell within ±50 m of the designated band. Plots were a minimum of 500 m apart. The physical environment of the region and the plots is summarised by Ashton *et al*. (this volume). A 20 × 20 m vegetation reference plot was established at each location, and results from these surveys are in Ashton *et al*. (this volume).

Sampling at Eungella

On two occasions (November 2013 and March 2014), moths were sampled at Eungella using Pennsylvania-style light traps modified for use in rainforest conditions (Kitching *et al*., 2005). These traps comprise a vertically placed UV-dominant fluorescent tube powered by a 12-volt battery and surrounded by three transparent Perspex vanes. Moths attracted to the light are knocked down by the vanes and collected in a bucket suspended beneath. At each location, traps were hung at both head height and in the canopy above (after ropes had been suspended there with the aid of a bow and line-throwing arrows). Traps were open all night for three, usually consecutive, nights at each location. Ground and canopy were sampled simultaneously at each location. All moths with a forewing length greater than 1 cm were removed from the catches each day and sorted to 'morphospecies' (i.e. 'species' that exhibited repeatedly recognisable appearances). In the case of the readily recognisable Pyraloidea, any smaller individuals within the samples were also removed and sorted. A reference collection of spread and dried specimens was accumulated during this process.

Analysis of the Eungella Data

Pyraloid species were extracted from the larger Eungella moth dataset (Odell *et al*., 2016) to create a 'pyraloid dataset' for each season. This comprised site- and season-specific counts for each morphospecies identified as belonging to either the Pyralidae or Crambidae. Ground and canopy samples were pooled across the three trap nights to form single data points for each site in each season. Counts for each location and season were (log+1) transformed before analysis in order to de-emphasise the few very abundant species (and remove the problem of zero counts for rare species).

Species accumulation curves with associated 95% confidence intervals were generated using the 'vegan' package in R.

Non-metric multidimensional scaling (nMDS) ordinations based on a Bray-Curtis similarity index (Clarke & Gorley, 2006) were calculated using 100 random restarts. Species having the greatest effect on the overall patterns across elevational zones were identified by calculating Pearson's correlation coefficient, selecting species showing values of ±0.69 or more (Gerstman, 2003).

Comparative Data

Earlier studies at other rainforest locations using comparable traps and sampling methodologies have resulted in extensive collections, the data from which are used in this paper to place the Eungella species in their geographical context (at least in terms of our samples). These can be grouped into studies as follows:

Cape Tribulation (16.1°S 145.5°E)

Following earlier, more or less casual collecting activities at Cape Tribulation in the 1980s and 1990s, a one-hectare reference plot was established adjacent to the site of the canopy crane facility in 2000. The vegetation of this site was described by Laidlaw *et al.* (2007). Four light traps were run for four nights within the one hectare during this survey. Considerably later, the canopy crane site itself was the location for a vertically stratified survey in which five traps were disposed at 10 m vertical intervals over a three-week period on two occasions (January and July 2012). Moth data from this survey remain unpublished, but methodological details can be found in the paper by Stork *et al.* (2016) which describes the beetle fauna from the same study.

Atherton Tablelands (ca 17.1°S 145.4°E)

The basis for our data from Atherton are the very extensive collections described by Kitching *et al.* (2000), and Orr & Kitching (1999, 2003). That study, based on a survey of 15,600 individual moths (again focusing on macro-moths and Pyraloidea), showed that the quality of rainforest remnants on basalt was reflected in the assemblage structure of the moth species occurring within them. Additional, unpublished surveys were also carried out on other substrate types within the region. Further surveys were made in 2010–2011, assessing the fauna at the 25 ha reference site established by the CSIRO at Robson Creek (17.1°S 145.5°E). Over 1500 moths were collected and sorted over three seasonally contrasting field trips. The tree flora of the Robson Creek site has been described by Bradford *et al.* (2014).

Mount Lewis (16.3°S 145.2°E)

Extensive moth surveys were carried out within the forest at Mt Lewis in far northern Queensland in November 2009 and April 2011. As with the Eungella survey, this study established replicated sampling sites along an elevational gradient. A total of 20 sites was assessed on each occasion. A total of 17,200 moths of 1134 species was examined and analysed. The results are presented in Ashton *et al.* (2016).

Paluma (18.6°S 146.1°E)

A one-hectare reference plot was established at Paluma in 1999. All trees greater than 5 cm diameter at breast height were surveyed (see Laidlaw *et al*., 2007) and various insect traps operated over a three-week period. These included four moth traps opened over a three-night period. Only a modest number of moths was collected (<2000 individuals) and the survey was not repeated.

Tamborine (27.9°S 153.2°E)

As part of a 2017–2018 'bioblitz', moths were sampled within patches of both rainforest and wet sclerophyll vegetation at Thunderbird Park, Mt Tamborine (Kitching *et al.*, in press). Light traps were operated at six sites (three in rainforest, three in wet sclerophyll) on each of two occasions, October 2017 and March 2018. A total of 1726 moths was collected.

Lamington National Park (28.1°S 153.1°E)/Border Ranges National Park (28.2°S 153.1°E)

Twenty reference sites were established along an elevational gradient at both Lamington National Park and Border Ranges National Park (both located within the McPherson Range straddling the Queensland/NSW border). For each transect, four replicate sites were established at each 200 m elevational band from 300 m asl to 1100 m asl. The same protocol as was applied at Eungella was carried out at both these locations: indeed, the protocol applied at Eungella was consciously based on these earlier surveys (and that at Mt Lewis). At Lamington, the sites were surveyed for moths in October 2006 and March 2007, resulting in an assessment of 11,300 individuals of 860+ species (Kitching *et al.*, 2011; Ashton *et al.*, 2011). The Border Ranges transect was sampled in April and November 2010, resulting in catches of 40,850 individuals of 612 species (Ashton *et al.*, 2016).

All reference collections either have been or will be deposited in the Queensland Museum.

Identification

An attempt has been made to identify all members of the Pyraustinae and Spilomelinae from our samples to the species level based on their phenotypes (i.e. without genitalic dissections or molecular barcoding). This is a challenging task in the absence of illustrated monographs. Fortunately, virtually all named species and those identified but not yet formally named within the incomparable Australian National Insect Collection (ANIC) have been barcoded and the results uploaded to the international BOLD website (http://www.boldsystems.org/). This procedure requires that a photograph of each specimen so analysed accompany the on-line molecular data. This resource, in principle, allows almost all known species to be identified by comparison with the photographs, although this remains an arduous and painstaking task. The additional websites maintained by Don Herbison-Evans and Stella Crossley (http://lepidoptera.butterflyhouse.com.au/) and that associated with the ANIC itself (http://amo.ala.org.au/) are also very useful. Those species in our Eungella collections which also occurred in our early studies on the Atherton Tablelands had been identified by one of us (AGO) by direct comparison with the ANIC collection (see Orr & Kitching, 1999, 2003). Some genera, notably *Nacoleia* and *Metasia* within the Spilomelinae, await much needed revision and present particular challenges and uncertainties in identification.

RESULTS AND DISCUSSION

Table 1 summarises the number of specimens of Pyraloidea encountered at each elevation in the two seasons sampled, with the percentage that each catch represented of the entire moth sample encountered. A total of 2488 pyraloids was sampled in the spring (November), representing 24.7% of our entire sample. Pyraloids were more dominant in the lowland samples (almost 50% of moths encountered at the lowest (200 m) sites) but still represented an eighth of all moths encountered, even at the 1200 m sites. For the late summer (April) samples, 4831 pyraloids were sorted, representing more than 35% of all moths in our surveys. In contrast to the spring samples, numbers were more evenly spread across elevations.

TABLE 1. Numbers (and percentages) of Pyraloidea in spring (November) and late summer (March) samples.

Elevation (m above sea level)	Spring samples	Summer samples
200	789 (49.5%)	728 (44.7%)
400	743 (40.3%)	1065 (44.1%)
600	338 (26.9%)	1223 (43.9%)
800	228 (8.4%)	896 (23.5%)
1000	255 (16.4%)	407 (26.7%)
1200	135 (12.5%)	512 (32.3%)
Overall	**2488 (24.7%)**	**4831 (35.2%)**

Species Accumulation Curves and Estimated Species Richness

Figure 1 shows the discovery curves for each of the two seasons' sampling, with associated 95% confidence estimates. In neither case did the curves reach an asymptote, suggesting more species remained to be found. Nevertheless, both showed 'healthy' declines in acceleration, indicating that our samples were adequate for the proposed analyses. The curve for both samples suggests a total richness of something over 130 species.

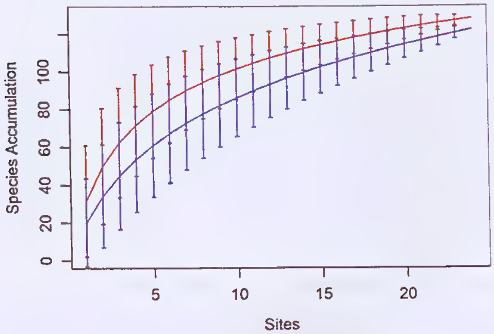


FIGURE 1. Species accumulation curves for spring (blue) and summer (red) samples for the Pyraloidea sampled at Eungella.

Patterns in the Assemblages of Pyraloidea

Figures 2a and 2b show the results of the multidimensional scaling analysis of the pyraloids sampled in spring (2a) and late summer (2b), respectively. Both ordinations show highly significant deviations from random admixture, and both show fundamentally similar patterns. In both spring and late summer, there are distinct assemblages of moth species indicated for both the lower and higher elevations, separating between about the 600–800 m elevations. In the spring (November) data, this distinction is very clear. With a few exceptions, the data points from each elevation cluster together and trend across the ordination plot. Whether this is due to the inevitably greater spatial proximity on the ground of the sites from the same elevational band, or is a real ecological pattern, is moot. Nevertheless, the clear lowland/upland distinction transcends these issues and we accept it as ecologically real. For the late summer (March) results, the lowland/upland separation is also clear, but one 800 m site blurs the clear distinction between lowland and upland.

Although the overall patterns shown by the pyraloid fauna were similar across the two seasons that we sampled, the particular species most highly correlated with these patterns differed except in one case.

Species That Correlate Strongly with the Overall Pattern

Table 2 lists those species for which patterns of occurrence correlated most strongly with the overall pattern for the super-family. Figures 3 and 4 show the patterns of occurrence for these species across the elevations sampled. For the spring samples, five species showed correlation coefficients higher than 0.69; for the late summer samples, four species met this criterion.

For the spring assemblage, four of the five highly correlated species were Crambidae-Spilomelinae, with the fifth being an acentropine (also Crambidae). Three of the five species are Australian endemics, with *Margarosticha sphenotis* and *Tetridia caletoralis* having widespread tropical Old World distributions. Figure 3a–e illustrates the abundances levels of each of these species at each of the elevations sampled. Three of the five species (Figures 3a, 3b & 3c) show that the species concerned were clearly associated with lowland sites. *Heterogramma holophaea* (Figure 3d) and *Nacoleia glageropa* (Figure 3e) occurred across all elevations but favoured higher (*N. glageropa*) and lower (*H. holophaea*) sites, respectively.

FIGURE 2. Visualisation of the data on Pyraloidea abundances using non-metric multidimensional scaling following calculation of Bray-Curtis similarities: (a) spring samples (November 2013); (b) late summer samples (March 2014).

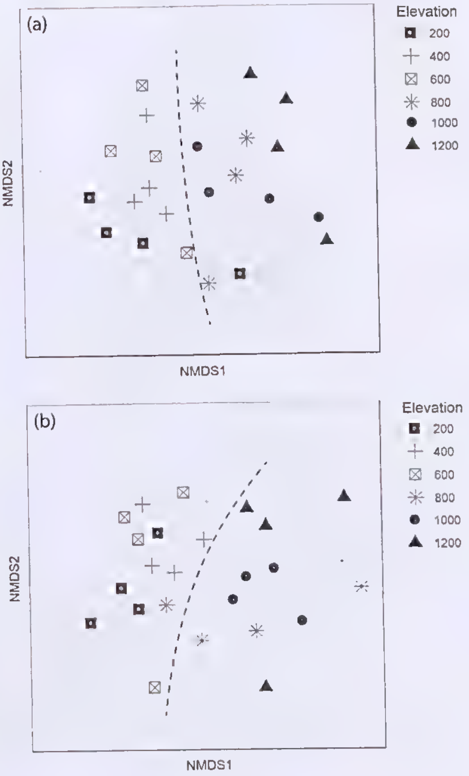
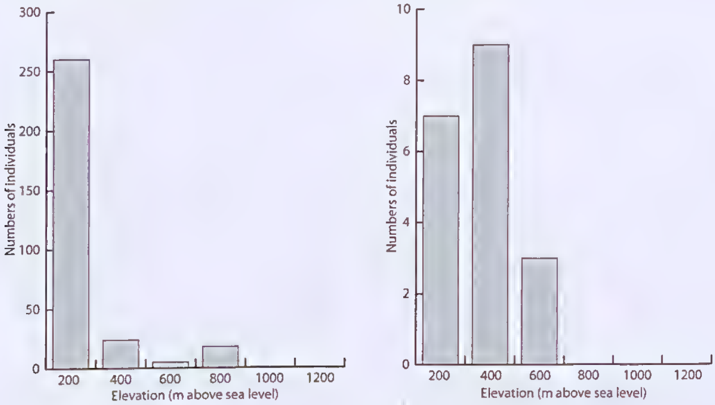
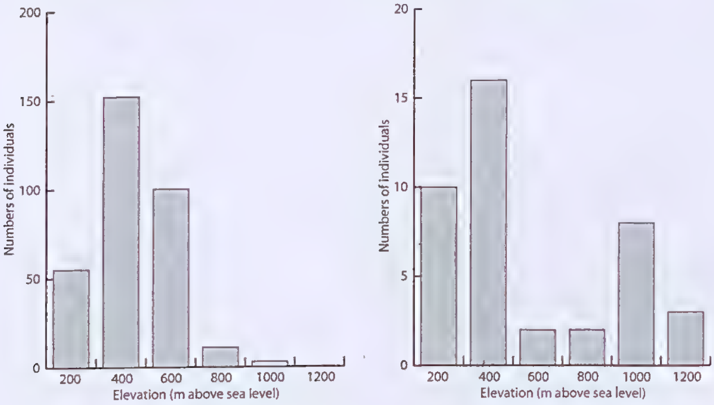


FIGURE 3. Species from the spring survey at Eungella National Park and Pelion State Forest, Queensland, that show a Pearson correlation with the overall ordination results >0.69: (a) *Margarosticha sphenotis* (Crambidae: Acentropinae); (b) *Tetridia caletoralis* (Crambidae: Spilomelinae); (c) *Parotis atlitalis* (Crambidae: Spilomelinae); (d) *Herpetogramma holophaea* (Crambidae: Spilomelinae); (e) *Nacoleia glageropa* (Crambidae: Spilomelinae).

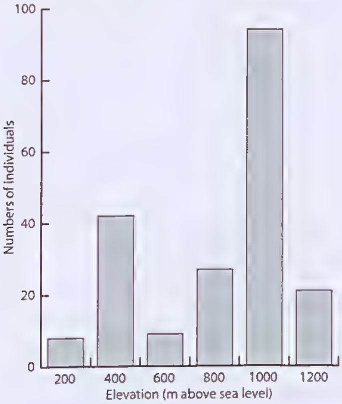
(a) *Margarosticha sphenotis* (b) *Tetridia caletoralis*



(c) *Parotis atlitalis* (d) *Herpetogramma holophaea*



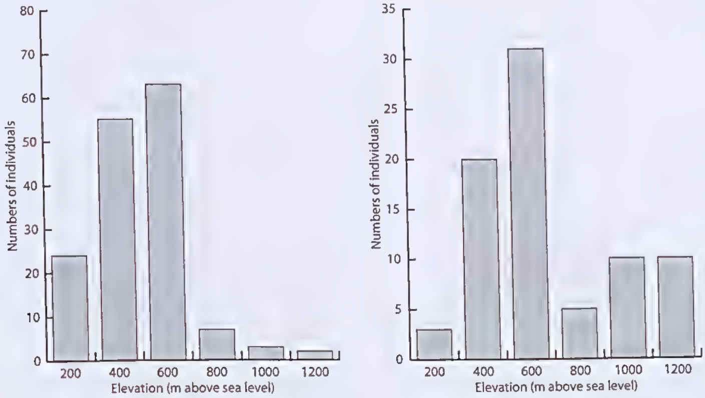
(e) *Nacoleia glageropa*



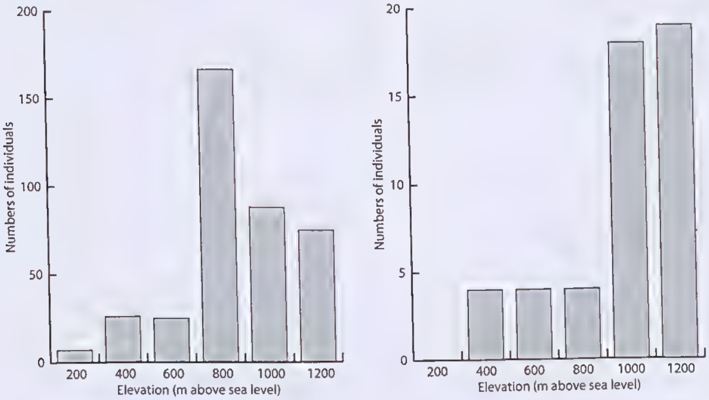
In the late summer samples, of the four species that correlated highy with the overall pattern (Figure 4), three are spilomelines with the fourth a pyraline pyralid. *Camptomastix hisbonalis* is widely distributed beyond Australia. *Nacoleia glageropa* is only known from Australia. The pyralid, *Endotricha pyrrhocosma*, is known from Queensland and Papua New Guinea. The distribution of *Palpita austrannulata* in Australia is hard to ascertain, as this species was separated from the widely distributed *P. annulata* relatively recently (Inoue, 1996) and many earlier records are under the old name. Figure 4a–d illustrates the abundances of these four species across elevations. All were found at each of the elevations but showed clear preferences. *Endotricha pyrrhocosma* (Figure 4a) favoured mid-elevations (400–600 m). *Palpita austrannulata* (Figure 4d) favoured the lower elevations. *Nacoleia glageropa* (Figure 4c) and *Camptomastix hisbonalis* (Figure 4e) favoured the higher elevations.

The patterns shown in Figures 3 and 4 inevitably reflect relative abundance as well as elevational preferences. The differences between the two seasons suggest that as the warmer, wetter summer progresses, so some species expand their populations to exploit the more mesic conditions. Only *Nacoleia glageropa* appeared to show preferences for higher elevations in both seasons. At all other locations at which we have encountered this species (from Lamington to the Atherton Tablelands, see Table 3), it has been at upland sites.

FIGURE 4. Species from the late summer survey at Eungella National Park and Pelion State Forest, Queensland, that show a Pearson correlation with the overall ordination results >0.69: (a) *Palpita austrannulatus* (Crambidae: Spilomelinae); (b) *Endotricha pyrrhocosma* (Pyralidae: Pyralinae); (c) *Nacoleia glageropa* (Crambidae: Spilomelinae); (d) *Camptomastix hisbonalis* (Crambidae: Spilomelinae).


(a) *Palpita austrannulata*

(b) *Endotricha pyrrhocosma*


(c) *Nacoleia glageropa*

(d) *Camptomastix hisbonalis*

TABLE 2. Pyraloid moth species from Eungella National Park that correlated highly (Pearson's $r > 0.69$) with the assemblage pattern shown by either MDS Axis1 or MDS Axis2 for the ordination of the entire pyraloid assemblage.

Species	**Family-subfamily**	**Pearson correlation**	**Biological notes**
SPRING SAMPLES			
Margarosticha sphenotis	Crambidae-Acentropinae	0.75	Aquatic larvae. Restricted to Australia (NSW, NT, QLD).
Tetridia caletoralis	Crambidae-Spilomelinae	0.69	Food-plants unknown in Australia, recorded from Dipterocarpaceae in Asia. Distributed from India and China to Queensland.
Parotis atlitalis	Crambidae-Spilomelinae	0.84	Larvae feed on *Glochidion* (Euphorbiaceae). Distributed from SE Asia to New South Wales.
Herpetogramma holophaea	Crambidae-Spilomelinae	−0.77	No food-plants known. Restricted to Australia (QLD).
Nacoleia glageropa	Crambidae-Spilomelinae	−0.76	No food-plants known. Restricted to Australia (QLD, NSW).
LATE SUMMER SAMPLES			
Palpita austrannulata	Crambidae-Spilomelinae	0.86	No food-plants known. Separated from widely distributed *annulata* by Inoue (1996).
Endotricha pyrrhocosma	Pyralidae-Pyralinae	−0.85	No food-plants known. Restricted to Queensland and PNG.
Nacoleia glageropa	Crambidae-Spilomelinae	−0.85	No food-plants known. Restricted to Australia (QLD, NSW).
Camptomastix hisbonalis	Crambidae-Spilomelinae	−0.78	No food-plants known. Widely distributed in eastern Asia. In Australia recorded from New South Wales and Queensland.

The Pyraustinae-Spilomelinae (P-S) Clade at Eungella and its Biogeographical Context

Table 3 lists those members of the Pyraustinae-Spilomelinae clade (*sensu* Regier *et al.*, 2012) identified from our Eungella samples. It further indicates which of these species were encountered in our various other studies at rainforest sites in Queensland (plus Border Ranges NP, NSW). It must be emphasised that this comparison (Columns 3–10) is based *only* on our collections. Further, many other species within the clade were encountered at sites other than Eungella; this table is solely an attempt to put the Eungella species into their broader context. Full results on the other sites will be published elsewhere. The final two columns indicate the broader distribution recorded for these species in Australia and beyond. These have been constructed using the databases available in *The Atlas of Living Australia* (https://www.ala.org.au/) and the BOLD website alluded to earlier (http://www.boldsystems.org/).

A total of 91 species of the P-S clade of Crambidae has been identified in our samples from Eungella. In itself this is remarkable, representing about 20% of the described Australian fauna. Of these 91, 28 species occurred, in addition, in our samples from both north and south of Eungella. Forty of the species occurred in our samples only from sites to the north of Eungella, and eight exclusively from more southerly sites. Finally, fifteen of the species encountered were unique to Eungella. We stress again that these patterns are based solely on our collections over the last two decades. With respect to the data from within Australia, however, we note that the sites we have examined to the south of Eungella have essentially all been in the same extended Border Ranges Massif and its outliers (Mt Tamborine, Lamington NP and Border Ranges NP). In contrast, the more northerly sites that we examined (Cape Tribulation, Mt Lewis, the Atherton Tablelands and Paluma) represent several rainforest isolates. There are small rainforest patches between Eungella and south-eastern Queensland: Kroombit Tops and the Conondale Ranges come to mind. The moth fauna of these locations awaits attention.

TABLE 3. Pyraustinae and Spilomelinae encountered in the Eungella Biodiversity Survey.
Note: Records in Columns 3–10 are based on presence or absence and ONLY on surveys by the Kitching Laboratory (see text).
Asterisked designations correspond to those in the BOLD database (see text).

GENUS	SPECIES	EUNGELLA	LAMINGTON	BORDER RANGES	TAMBORINE	PALUMA	ATHERTON TABLELANDS	MT LEWIS	CAPE TRIBULATION	PREVIOUS KNOWN AUSTRALIAN DISTRIBUTION (collated from *Atlas of Living Australia* and BOLD database)	KNOWN WIDER DISTRIBUTION (collated from BOLD database)
Pyraustinae											
Ebulea	*epicroca*	■	■							SE Queensland	none
Hyalobathra	*miniosalis*	■			■		■	■		Sunshine Coast to Cape York	none
Hyalobathra	*crenulata*	■		■	■					QLD/NSW Border to Cape York	none
Uresiphita	*ornithopteralis*	■	■	■			■			Throughout; Norfolk Island	none
Spilomelinae											
Aethaloessa	*calidalis*	■	■				■			SE Queensland to Cape York	East & SE Asia; Pacific
Agathodes	*paliscia*	■	■							SE Queensland; Western Australia	none
Agrioglypta	*eurytusalis*	■						■	■	Cairns region	Tropical & subtropical Asia
Agrioglypta	*zelimalis*	■						■	■	Sunshine Coast to Cape York	Tropical Asia; New Caledonia
Agrioglypta	*itysalis*	■						■	■	Far northern Queensland	Tropical Asia
Agrioglypta	*excelsalis*	■		■	■			■		Cape York	Tropical Asia
Analyta	*apicalis*	■								Cape York	India; Sri Lanka; Taiwan
Archernis	*callixantha*	■	■	■		■	■			Southern NSW to Townsville	New Guinea
Arthroschista	*hilaralis*	■						■		SE Queensland to Cairns	East & SE Asia
Ategumia	*adipalpis*	■								SE Queensland	India; China; Japan; SE Asia
Bradina	*mannusalis*	■					■			SE Queensland	none
Camptomastix	*hisbonalis*	■								SE Queensland	China to PNG

GENUS	SPECIES	EUNGELLA	LAMINGTON	BORDER RANGES	TAMBORINE	PALUMA	ATHERTON TABLELANDS	MT LEWIS	CAPE TRIBULATION	PREVIOUS KNOWN AUSTRALIAN DISTRIBUTION (collated from *Atlas of Living Australia* and BOLD database)	KNOWN WIDER DISTRIBUTION (collated from BOLD database)
Chabula	*acamaselis*	■	■	■						SE Queensland	Tropical and subtropical Asia
Cirrhocrista	*brizoalis*	■	■	■					■	Coastal: All Queensland	India to Taiwan; SE Asia; New Guinea
Cirrhocrista	*aetherialis*	■						■	■	Central to far northern Queensland	none
Cnaphalocrocis	*medinalis*	■	■	■	■		■			Central NSW to NT	East & SE Asia; a widespread pest
Cnaphalocrocis	*bilinealis*	■					■			SE Queensland to Cape York	Africa; China; Sri Lanka; SE Asia
Conogethes	*punctiferalis*	■					■	■	■	Adelaide; southern NSW to Kimberleys	Indian subcontinent; SE Asia; pest of fruit
Conogethes	*haemactalis*	■					■	■		Northern NSW to Cape York	no information
Conogethes	*pluto*	■						■		Coastal: SE Queensland to NT	SE Asia; Solomons
Cotachena	*histricalis*	■								Tropical Queensland	Indonesia; Solomons; New Guinea
Cotachena	*aluensis*	■				■	■	■		Far northern Queensland	Solomons
Diaphania	*indica*	■		■			■	■		West, north and east coasts	Southern Asia; worldwide pest
Dracaenura	*horochroa*	■								Cape York	New Guinea
Dysallacta	*negatalis*	■								SE Queensland to Townsville	Tropical and subtropical Asia; Africa
Dysallacta	ANIC1*	■	■				■			unpublished	none
Ectadiosoma	*straminea*	■					■	■		SE Queensland; tropical Queensland	none
Eurybela	*trophoessa*	■								Victoria to Queensland	none
Eusabena	*monostictalis*	■								Cape York	Ambon; New Guinea
Glauconoe	*deductalis*	■					■	■	■	Far northern Queensland	Sri Lanka; Taiwan; New Guinea
Glycythyma	*chrysorycta*	■					■	■		Sunshine Coast to Cape York	India to Japan
Glyphodes	*onychinalis*	■	■						■	SE to central Queensland	Tropical & subtropical Asia; Africa; Pacific

GENUS	SPECIES	EUNGELLA	LAMINGTON	BORDER RANGES	TAMBORINE	PALUMA	ATHERTON TABLELANDS	MT LEWIS	CAPE TRIBULATION	PREVIOUS KNOWN AUSTRALIAN DISTRIBUTION (collated from *Atlas of Living Australia* and BOLD database)	KNOWN WIDER DISTRIBUTION (collated from BOLD database)
Glyphodes	*multilinealis*	■					■	■		Tropical Queensland	New Guinea; Pacific Islands; Japan
Glyphodes	*stolalis*	■				■	■	■	■	Eungella northwards to NE Australia	Tropical & subtropical Asia; Africa; Indian Ocean Islands
Glyphodes	*cosmarcha*	■		■			■	■		SE Queensland, NSW	Thailand; PNG
Glyphodes	*caesalis*	■					■	■		Cairns northwards	Tropical & subtropical Asia; New Guinea
Glyphodes	*canthusalis*	■	■	■		■		■	■	Central NSW to Cape York	Tropical & subtropical Asia
Glyphodes	*conjunctalis*	■					■	■		Far northern Queensland	New Guinea; Molluccas
Glyphodes	*microta*	■	■				■	■		Central NSW to Cape York	none
Glyphodes	*flavizonalis*	■	■	■		■	■	■	■	Coastal: Northern NSW to Cape York	none
Haritalodes	*derogata*	■	■	■	■		■			Coastal: Sydney to Townsville	Africa; East & SE Asia; New Guinea
Herpetogramma	*licarsisalis*	■	■		■					Coastal: SE NSW northwards, and westwards to Perth	Old World Tropics
Herpetogramma	*holophaea*	■								Queensland; NT	none
Herpetogramma	*stultalis*	■					■	■		SE Queensland	Africa; East & SE Asia; New Guinea
Herpetogramma	cf *stultalis*	■								n/a	n/a
Herpetogramma	*hipponalis*	■						■		Far northern Queensland; NT	East Asia; Guadalcanal; New Guinea
Herpetogramma	*cynaralis*	■		■	■		■	■		Southern NSW to SE Queensland	Japan; Sri Lanka; SE Asia
Herpetogramma	*exculta*	■								SE Queensland; far NE NSW	none
Hymenoptychis	*sordida*	■					■		■	Northern Queensland	Tropical & subtropical Asia; Africa; Pacific
Maruca	*vitrata*	■	■		■			■	■	Coastal: Central NSW; Queensland; NT	Pantropical
Merodictya	*marmorata*	■	■	■	■					Coastal: Victoria to Cairns	none

GENUS	SPECIES	EUNGELLA	LAMINGTON	BORDER RANGES	TAMBORINE	PALUMA	ATHERTON TABLELANDS	MT LEWIS	CAPE TRIBULATION	PREVIOUS KNOWN AUSTRALIAN DISTRIBUTION (collated from *Atlas of Living Australia* and BOLD database)	KNOWN WIDER DISTRIBUTION (collated from BOLD database)
Nacoleia	*amphicedalis*	●					●			QLD/NSW Border to Cape York	none
Nacoleia	*glageropa*	●	●		●	●	●	●		SE Queensland	none
Notarcha	*aurolinealis*	●	●		●	●	●	●		Central NSW to Cairns	Hong Kong; SE Asia
Omiodes	*origoalis*	●					●	●		no information	NE India; SE Asia
Omiodes	*nigriscripta*	●			●				●	Townsville northwards	New Guinea
Omiodes	*diemenalis*	●	●	●	●		●	●		Coastal: Central NSW northwards to Queensland, NT	East & SE Asia, New Guinea, Pacific
Palpita	*austrounionalis*	●	●				●	●	●	Cape York	New Guinea
Palpita	*austrannulata*	●						●	●	Cape York, NT	none
Palpita	*limbata*	●	●	●	●			●	●	Central NSW northwards	Rennell Island; Guadalcanal
Palpita	*margaritacea*	●			●	●	●	●	●	Coastal: Victoria to SE Queensland	none
Parotis	*suralis*	●			●			●		Coastal: Central Queensland	West Pacific Rim
Parotis	*incurvata*	●						●		NE NSW; SE Queensland	Loyalty Islands; SE Asia
Parotis	*atlitalis*	●	●	●	●	●	●	●		NE NSW; south central Queensland	SE Asia
Piletocera	*meekii*	●					●		●	Central Australia (and elsewhere?)	Indonesia
Pleuroptya	*symphonodes*	●			●		●	●		Cape York	none
Pleuroptya	*balteata*	●	●	●						NE NSW; SE Queensland	Temperate & tropical Old World
Pleuroptya	ANIC2*	●						●	●	n/a	n/a
Prooedema	*inscisalis*	●	●		●				●	Coastal: All Queensland	India; China; SE Asia; New Guinea
Prophantis	*adusta*	●				●	●	●	●	Far northern Queensland	India; China; Japan; SE Asia; New Guinea

GENUS	SPECIES	EUNGELLA	LAMINGTON	BORDER RANGES	TAMBORINE	PALUMA	ATHERTON TABLELANDS	MT LEWIS	CAPE TRIBULATION	PREVIOUS KNOWN AUSTRALIAN DISTRIBUTION (collated from *Atlas of Living Australia* and BOLD database)	KNOWN WIDER DISTRIBUTION (collated from BOLD database)
Prorodes	*mimica*	■	■	■	■		■		■	SE Queensland	India; SE Asia; New Guinea
Protonoceras	*leucocosma*	■								Coastal: SE NSW to NT	none
Pygospila	*bivittalis*	■						■		Cape York; Darwin	India; China; SE Asia; New Guinea
Pygospila	*tyres*	■					■	■		Coastal: Queensland; NT	India; China; SE Asia
Rehimena	*auritincta*	■								Queensland; NW Australia	none
Rehimena	*leptophaes*	■								NSW; ACT; Queensland	none
Rhimphalea	*sceletalis*	■	■		■					Coastal: All Queensland	Old World tropics
Sameodes	*cancellalis*	■					■	■	■	Queensland to Cape York	Tropical & subtropical Asia; Africa; Pacific
Sisyrophora	*pfeifferae*	■								Eungella to Cape York	India; Taiwan; SE Asia
Spoladea	*recurvalis*	■	■				■	■		Throughout; Christmas Island	Cosmopolitan; mostly tropical
Stemorrhages	*amphitritalis*	■				■	■	■		SE Queensland	India; SE Asia
Stemorrhages	*marthesiusalis*	■						■		NE NSW; SE Queensland	India; Sri Lanka
Syllepte	*ochrotozona*	■		■	■	■	■	■		Coastal: Central Queensland northwards	none
Talanga	*sabacusalis*	■					■	■		Townsville northwards	SE Asia; New Guinea
Talanga	*sexpunctalis*	■	■	■			■	■	■	Northern NSW	SE Asia; New Guinea (unresolved species complex)
Terastia	*subjectalis*	■			■		■			NE NSW; SE Queensland	Indian and Pacific Ocean margins
Tetridia	*caletoralis*	■				■			■	Cape York	India; Sri Lanka; China; Japan; SE Asia; New Guinea

Comparing our results with what is known from other records and databases both within Australia and beyond, we can identify situations where Eungella is the northernmost known point of the species' distribution or, conversely, its southernmost point. For 24 species, Eungella appears to represent the species' southern limit, either in Australia and/or beyond. For five species, our Eungella records represent the northernmost incidence known. We stress that these results are necessarily limited by the quality of the databases on which they are founded (and, indeed, on the quality of our collection data). Nevertheless, it confirms the idea that Eungella represents the point of contact between southern and northern faunas, with the tropical faunas predominating. The number of Australian endemics among our list (just 23 out of 91) is unusually low. Adding the seven species we encountered which also occur in the Australasian islands to the north (New Guinea, Solomons, Moluccas), we still only find about a third of species which are endemic to the biogeographic region. This suggests that the Pyraloidea (or at least that section within which our fauna belongs) is predominantly a clade of the Old World tropics, with our fauna having many Oriental affinities.

We commend the P-S clade for further attention by future workers. Not only are its members attractive and common, they are relatively large as 'micros' go and a majority can be recognised on the basis of wing patterns alone. Clearly some genera are in need of more detailed taxonomic analysis and, in this regard, some of our identifications must be regarded as tentative.

ACKNOWLEDGEMENTS

Our studies at Eungella were funded initially under a Queensland/Chinese Academy of Sciences grant, with financial contributions from both the Queensland Government and the Chinese Academy of Sciences. This funding was complemented by a generous grant from the Mackay Regional Council drawn from funds generated by environmental levies. General support and staff contributions were made by Griffith University and the Queensland Museum. In the field we were supported by many local volunteers who have been acknowledged elsewhere.

Comparative collections made in other rainforest areas have been funded over many years by a wide range of other funding bodies and organisations. These are acknowledged individually in earlier papers.

We are grateful to all of these supporters.

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THE AMPHIBIAN FAUNA OF EUNGELLA AND THEIR IMPORTANT ROLE IN UNRAVELLING THE EVOLUTIONARY HISTORY OF THE AUSTRALIAN EAST COAST CLOSED FOREST BIOTA

MAHONY, M. J.[1]

The species diversity and endemism of the amphibians of the closed forest habitats at Eungella are assessed in the context of surrounding bioregions. The Central Mackay Coast bioregion in which Eungella occurs has a relatively high diversity of frogs, with 24 species from three native families: 5 species of Limnodynastidae, 7 Myobatrachidae, and 12 Pelodryadidae. The closed forest communities support a high level of phylogenetic endemism, with representatives of three ancient lineages of myobatrachids: one species of *Rheobatrachus*, two *Taudactylus*, and a disjunct population of a species of *Mixophyes*. In addition, it supports disjunct populations of several species of the genus *Litoria*. This high level of endemism is indicative of the importance of the upland rainforests of Eungella as a cool and moist refuge that has persisted over many millions of years.

Keywords: Eungella, Amphibia

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INTRODUCTION

Eungella, and the Clarke Range in which it occurs in mid-eastern Queensland, holds a special place in understanding the evolution of Australia's amphibian fauna due to its high phylogenetic endemism and species diversity. Unravelling and telling that story requires that we quantify its significance and place it into the larger context of the evolutionary history of the biota of eastern Australia. The aim of this study is to consider the amphibian fauna of Eungella National Park (Clarke Range) in broad biogeographic and evolutionary contexts, which together will lead to a deeper appreciation of why further research of its importance and intrinsic value is required. The outcome also serves to strengthen the conservation significance of the area.

For many decades Australian biologists have focused attention on species richness and endemism in the arc of rainforest that occurs as a series of disjunct blocks associated with the Great Dividing Range and eastern uplands of Australia. Attention is drawn to two important biogeographic features. First is that the mesic biome, which encompasses rainforest elements, was the ancestral vegetation of Australia; and, second, that expansion of drier-adapted sclerophyllous flora occurred as the climate dried and became warmer as the Australian continent drifted northwards over the past 30 to 50 Myr (Crisp *et al.*, 2001; Hill, 2004). Consequently, mesic communities contracted to near coastal mountains that receive high annual rainfall and now function as refugia (Crisp *et al.*, 2001). To reflect their historical connection and the process of climate warming and drying, these have been termed climate relicts (Hampe & Jump, 2011; Rosauer *et al.*, 2015). While most emphasis has been placed on identifying the location and biotic composition of these refugia, there has also been a focus on the role of the geographic barriers or gaps that separate them (Byrne *et al.*, 2008, 2011; Bryant & Krosch, 2016). More recently, the investigation of biotic composition has involved testing of specific evolutionary hypotheses based on the comparative phylogenetic pattern of taxa (species and populations) that have disjunct distributions in the refugia (Joseph & Moritz, 1994; Joseph *et al.*, 1995; Stuart-Fox *et al.*, 2001; Mahony *et al.*, 2006; Catullo & Keogh, 2014). These studies have uncovered common phylogeographic patterns, but they also demonstrate that different taxa show different responses to past environmental changes. Missing from these studies, which have included anurans, is the inclusion of taxa that have a deep evolutionary antiquity and which are represented in only a small number of the refugia. Inclusion of such taxa in comparisons is likely to be valuable since, because of their antiquity, the refugia are often disproportionately important for the conservation of the genetic diversity and phylogenetic history they represent (Rosauer *et al.*, 2009; Hampe & Jump, 2011).

To address this issue, this study focuses on the taxa of deeper genetic antiquity which form the endemic component of the amphibian fauna of Eungella National Park (NP). By necessity this analysis includes information on amphibian species richness and range limits among refugia.

METHODS

The focus of this study is on the biogeography of the anuran fauna of the closed forest vegetation communities at Eungella. The category 'closed forest' is used to maintain consistency with the terminology used in several reviews of the biogeography of eastern Australia (Byrne *et al.*, 2011; Bryant & Krosch, 2016). This category is equivalent to 'wet-forest' used in other descriptions such as that applied by Meyer *et al.* (this volume).

The analysis of anuran distribution is undertaken at the scale of the larger bioregional landscape unit (Thackway & Cresswell, 1995). The Eungella uplands are within the Central Mackay Coastal (CMC) bioregion. The largest areas of upland closed forests within this bioregion occur in Eungella NP. To assess the biogeographic context of the closed forest refugia for amphibians, a process of classifying species by taxonomy, distribution, forest preference and breeding biology has been adopted so that the analysis was biologically meaningful and tractable. Accordingly, the geographic analysis was restricted to all presence records for amphibians from the *Atlas of Living Australia* (ALA), for the bioregions (Thackway & Cresswell, 1995) that include the Central Mackay Coast (CMC) and the two adjacent bioregions to the north, south and west based on IBRA7 mapping (https://www.environment.gov.au/land/nrs/science/ibra).

The data-set was therefore restricted to the Central Mackay Coast (CMC), the Brigalow Belt North (BBN) (that surrounds the CMC on its north, south and west), Southern Eastern Queensland (SEQ) (further south), Brigalow Belt South (BBS) (further south-west), Wet Tropics (WT) (further north), Einasleigh Upland (EU) (further north-west), and Desert Upland (DU) (further west) bioregions (Figure 1). Some reference is also made to an isolated closed forest refugium at Kroombit Tops, which is to the south-east of Eungella and is within the SEQ bioregion.

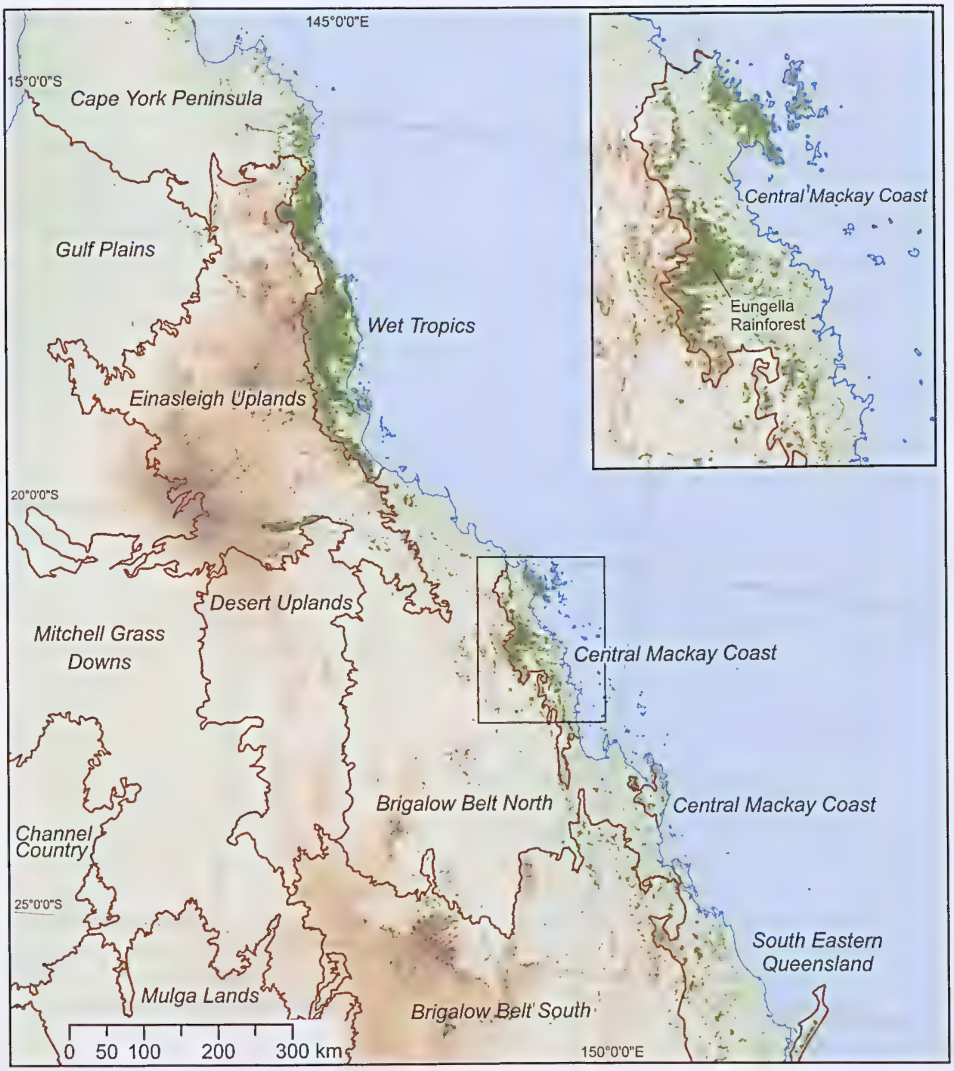
Throughout, reference is made to the names of barriers of low-lying country that separate the closed forest refugia (see Bryant & Krosch, 2016), including the 'Burdekin Gap' between the CMC and the WT bioregions, which corresponds to the lower Burdekin River drainage, and the 'St Lawrence Gap' between the CMC and SEQ bioregions that corresponds to the lower Fitzroy River drainage. For the quantitative assessment, the refugia and gaps are considered at the landscape scale using the bioregional approach.

There is considerable debate surrounding the higher taxonomic nomenclature among the Australian ground frogs and tree frogs (Frost *et al.*, 2006; Duellman *et al.*, 2016). For the ground frogs, although all are recognised as belonging to a southern hemisphere clade of Gondwanan origin (superfamily Myobatrachoidea), several familial and subfamilial classifications have been proposed (Heyer & Liem, 1976; Farris *et al.*, 1982; Frost *et al.*, 2006). Because there is instability in usage, I have chosen to adopt a conservative approach and follow the taxonomy described by Frost *et al.* (2006). The ground frogs are placed into two families, the Limnodynastidae (8 genera) and Myobatrachidae (13 genera), with *Mixophyes* and *Rheobatrachus* (formerly Rheobatrachidae of Heyer & Liem, 1976) placed in the Myobatrachidae. The phylogenetic analysis of Frost *et. al.* (2006) placed these two genera as a sister lineage to all myobatrachid frogs. Read *et al.* (2001) provided a phylogenetic study of myobatrachid frogs that assumed monophyly of the group and used only *Limnodynastes* to root the tree and, therefore, did not consider the relationships of *Mixophyes* and *Rheobatrachus*. Their analysis provided strong support for the position that *Taudactylus* was the sister lineage to all the other myobatrachid frogs they tested. The important point for this study is that, whatever classification is adopted, the ground frogs are old endemics with a long evolutionary history in Australia. Furthermore, in phylogenetic analyses several of the important Eungella taxa are shown to be basal in the topology of the family tree and have long evolutionary lineages.

In contrast, the numerically large Australo-Papuan tree frog family, Pelodryadidae, is divided into three genera, *Litoria* (166 species), *Cyclorana* (13 species, restricted to Australia) and *Nyctimystes* (26 species, restricted to Papua New Guinea), although there is also considerable debate about generic level subdivision of *Litoria* (Duellman *et al.*, 2016). To simplify comparisons of geographic distribution in the analysis, here the intra-generic 'species groups' of *Litoria*, defined by Tyler & Davies (1978) and based on morphology and behaviour, are used.

All ALA records were scrutinised, and those records that failed two of the filters applied to indicate validity in the Atlas were removed as potentially spurious. There are numerous sources of bias that occur in atlas records, and it is not possible to account for all of them. The approach taken was to accept that the majority of records provide a good overall picture of species distribution, and to scrutinise outliers based on expert knowledge of distribution and habitat preferences of the specific taxon. Undoubtedly, there are some spurious records that have been included in the analysis since the correct species identification of some records, particularly those that are geographic outliers, can pose a significant problem if vouchers are not available in museum collections to support the observations. For the primary objective of this study, however, these records do not involve the significant anuran fauna that occur as endemic or disjunct populations in the closed forest at Eungella.

FIGURE 1. Mid-eastern Queensland with elevation (light colouring), rainforest vegetation communities (green) and the bioregions used in the comparisons of anuran distributions. Inset shows the distribution of rainforest and altitude at Eungella. The rainforest distribution is derived from the *Atlas of Living Australia* (NVIS 41. Major Vegetation Groups).



To enable a comparison of the anuran fauna among the refugia, records were divided into those found in closed forest vegetation communities (rainforest and wet sclerophyll forest) and those in open forest vegetation communities (dry sclerophyll forests, savannah woodlands, grasslands and heath communities). Species records were then scored by the bioregions in which they occurred, followed by their breeding habitat – predominantly lotic (stream), lentic (ponds, swamps and ephemeral pools), or direct development. For the majority of frog species, it is relatively straightforward to place them into the categories of closed or open forest dwellers. There are several species, however, for which this subdivision is difficult and possibly controversial, and these tend to be those species that are common and widespread generalists. I have applied a threshold of 80% of records (based on expert opinion) to categorise these species. *Litoria wilcoxii*, for example, is associated with the riparian zone of permanent watercourses. Streams that this frog occupies at higher altitude may be flowing through closed forest, while at lower altitude it may be predominantly open forests. Nevertheless, the riparian zone may include closed forest elements, and the frogs occupy a stream habitat that provides moisture through all seasons. My observations are that this frog will penetrate into closed forests (e.g. rainforest), but it is most abundant in streams in open forests (supported by observations by Meyer *et. al.*, this volume). In contrast, its close sibling species, *L. jungguy*, is most commonly found in stream habitats in closed forests in the WT bioregion.

Area of Occupancy (AAO) and Extent of Occupancy (EOO) are calculated for a small number of species following the IUCN Red List approach (IUCN 2006), and the AOO is based on a 0.02 degree grid and the EOO on a minimum convex polygon.

RESULTS

The Central Mackay Coast bioregion (CMC) has a relatively high diversity of frogs, with 24 species from three native families, 5 species of Limnodynastidae, 7 Myobatrachidae and 12 Pelodryadidae (Table 1).

Three anuran species are endemic to the CMC bioregion, and all are myobatrachids that are restricted to the closed forests of the Eungella escarpment and tablelands. One of these species, *Rheobatrachus vitellinus*, is presumed to be extinct, and *Taudactylus eungellensis* has suffered serious declines in distribution in the past 30 years (see Meyer *et. al.*, this volume). These species occur in close association with stream habitats, with the third endemic species, *T. liemi*, often found in seepages and rock scree at the edge of streams and not directly in pools or riffles in the stream. Each of these species has a derived breeding biology: *Rheobatrachus* has direct development of the tadpoles and is a gastric brooder, and the *Taudactylus* species deposit a small number of large, yolky eggs beneath rocks or deep in crevices, and the tadpole stage is free living. *Rheobatrachus* showed, and *T. eungellensis* shows, strong morphological and behavioural adaptations to living in fast-flowing streams. There are no members of these genera in the habitats of the hot and drier open forest/savannah communities of the BBN bioregion to the north, south and west of the CMC bioregion, but they do have conspecifics in closed forest in the further removed WT bioregion to the north (*Taudactylus*) and SEQ bioregion to the south (*Rheobatrachus* and *Taudactylus*).

Not only are these species endemic to the CMC bioregion, but their distributions are tightly limited to the fast-flowing streams of the tableland and escarpment at Eungella, such that their area of occupancy (AOO) and Extent of Occupancy (EEO) are among the smallest of Australian frogs (Table 2). *Rheobatrachus vitellinus* occurred only at Eungella, and its congener *R. silus* (also presumed extinct), was restricted to closed forest habitats in the Conondale and Blackall Ranges in the SEQ bioregion, to the south of the St Lawrence Gap (Table 1). Both have very restricted ranges; the AOO are 108 and 48 sq. km, and EOO are 753 and 98 sq. km, respectively. There is no record of this genus in the WT bioregion to the north of the Burdekin Gap, despite this area supporting a much larger area of closed forest than that at Eungella.

Species of the genus *Taudactylus* are closely associated with recognised closed forest refugia in eastern Australia. Two extant species occur at Eungella (CMC bioregion), two in the WT bioregion (considered extinct), and two in the SEQ bioregion (Table 1). The two species in the SEQ bioregion occupied separate, isolated refugia: *Taudactylus pleione* at Kroombit Tops to the south-west of Eungella, which is extant but critically endangered, and *T. diurnus* further south in the Conondale, Blackall and D'Aguilar Ranges. In the Conondale and Blackall Ranges, *T. diurnus* co-occurred with *R. silus*, and both are presumed extinct. Of the two species of *Taudactylus* that occurred in the WT bioregion, one (*T. acutirostris*) is presumed extinct, and the other (*T. rheophilus*) is listed as critically endangered (Table 1) with no known extant populations. Summarising, two species of *Rheobatrachus* and three species of *Taudactylus* that occurred in the refugia have disappeared, and two of the remaining three species of *Taudactylus* have been subject to declines in distribution and abundance within the small refuges where they occur (Table 1).

There are only two other species of myobatrachid and three species of pelodryadid that are classed as closed forest species in the CMC bioregion (Table 1). Among the myobatrachids, *Adelotus brevis* and *Mixophyes fasciolatus* have disjunct populations in the closed forests at Eungella, and the nearest populations occur to the south in the SEQ bioregion. Eungella represents the northernmost populations of these species, and neither occur in the WT bioregion to the north. Unlike *Rheobatrachus* and *Taudactylus*, populations of these species are widespread in closed forest habitats of the SEQ bioregion and further south in NSW. Both also occur as disjunct populations at Kroombit Tops, at the northern extent of the SEQ bioregion, to the south-east of Eungella.

Among the pelodryadids there is no species endemic to Eungella or the CMC bioregion (Table 1). Two species, *L. chloris* and *L. revelata*, classed as closed forest inhabitants, have disjunct populations at Eungella. I have classified both species as pond breeders ('lentic') although they are often encountered along streams, but where they do occur in the riparian zone they breed in slow-moving ponds or isolated rock pools (see Meyer *et. al.*, this volume). *Litoria chloris* will also often breed in small ephemeral pools away from the riparian zone. There are no records of this frog in the BBN bioregion, and the species does not occur in the WT bioregion where a sister sibling, *L. xanthomera*, occurs (Davies *et al.*, 1986). At Eungella, *L. revelata* is known only from high altitude on the plateau and escarpment, where it is associated with riparian habitats and human-constructed ponds. *Litoria revelata* has a disjunct population in the WT bioregion and is more widespread in the SEQ bioregion, but it does not have a population at Kroombit Tops. It has an extensive southern latitudinal distribution in closed forest habitats in eastern NSW.

The other seven species of *Litoria* with records in the CMC bioregion also occur in suitable habitats in the surrounding BBN bioregion, and these species are classed as habitat generalists. Apart from *L. wilcoxii*, none are stream specialists and none have tadpoles showing morphological adaptions to fast-flowing water. *Litoria wilcoxii* is widely distributed in streams that flow east from the Great Dividing Range from the Sydney Basin bioregion in the south to the WT bioregion, and occurs in most streams that have riparian vegetation. This frog occurs across the entire altitudinal range at Eungella, but is most common along slower-flowing open streams in the valley and on the tablelands, and is not common in the dense rainforest riparian zone or well adapted to the fast-flowing streams of the escarpment that are favoured by *Rheobatrachus* and *Taudactylus* (see Meyer *et. al.*, this volume).

Six species of myobatrachid frog (*Limnodynastes peronii*, *Limnodynastes terrareginae*, *Platyplectrum ornatum*, *Pseudophyrne raveni*, *Pseudophryne major* and *Uperoleia fusca*) that are not dependent on closed forest habitats, occur at Eungella, and all but one (*Limnodynastes terrareginae*) breed in pools and ephemeral habitats (Table 1). Four of these species (*L. peronii*, *P. ornantum*, *P. major* and *L. terrareginae*) also occur in the open woodland/savannah habitats of the BBN bioregion and have extensive distribution outside these bioregions. In the CMC bioregion, *Uperoleia fusca* occurs only in the far south in the moist forests of the Byfield area, with a disjunct population at higher altitude at Eungella. This frog is common south of the St Lawrence Gap and along the eastern seaboard to southern NSW, where it is not a specialist of closed forest habitats. *Pseudophryne major* is also at the northern limit of its distribution in the CMC bioregion, and has a more extensive distribution to the south. This species does not penetrate into rainforest communities and is usually found in sclerophyll forest, both open and closed. A sibling species (*P. covacevichae*) occurs in the WT bioregion and is also associated with sclerophyll forest communities, not rainforest.

Closed forest refugia to the north and south of Eungella, in the WT and SEQ bioregions, also have high levels of species diversity and endemic anuran taxa (Table 1). The WT bioregion has 14 species of Microhylidae, and no species of this family are found south of this bioregion. Similarly, there is one species of the family Ranidae found in the WT bioregion and further north on Cape York. Evidently, the Burdekin Gap is a considerable barrier to southern dispersal of these frogs. Species in these families are widely accepted to have entered Australia from the north when the Australia continental plate collided with the Asia plate.

There are five species of myobatrachid frogs that are endemic to the WT bioregion (3 species of *Mixophyes*, and 2 species of *Taudactylus*). One species of *Pseudophryne* (*P. covacevichae*) is found mostly in the bioregion but has some populations in the adjacent western Einsleigh Uplands bioregion. No genus of myobatrachid is endemic to the WT bioregion.

TABLE 1. Frogs of Eungella and the surrounding bioregions classified into closed forest and open forest habitats, and by breeding location. The uplands of Eungella are dominated by closed rainforest and wet sclerophyll vegetation communities due to the high annual rainfall, whereas the lowlands are dominated by open forest communities with lower annual rainfall. Species are arranged with those occurring in the Eungella Central Mackay Coast bioregion listed first, followed by the other bioregions. To emphasise the importance of the high rainfall habitats, they are presented in the first column. Conservation Status is based on the National *Environmental Protection and Biodiversity Conservation Act* (2000) listing of threatened species, and categories follow the IUCN (2004) classification: *E* Extinct, *CE* Critically Endangered, *END* Endangered.

Species	**Closed Forest (rainforest and wet sclerophyll forest communities)**	**Open Forest communities**	**Wet Tropics bioregion**	**Brigalow Belt North bioregion**	**Eungella. Central Mackay Coast bioregion**	**South Eastern Queensland bioregion**	**Stream (lotic)**	**Pool (lentic)**	**Direct Development**	**Conservation status (EPBC Act)**
Rheobatrachus vitellinus	X				X		X			E
Taudactylus eungellensis	X				X		X			END
Taudactylus liemi	X				X		X			
Adelotus brevis	X				X	X	X	X		
Mixophyes fasciolatus	X				X	X	X			
Limnodynastes peronii		X	X	X	X	X	X	X		
Limnodynastes tasmaniensis			X	X	X	X		X		
Limnodynastes terraereginae		X		X	X	X	X	X		
Platyplectrum ornatum		X	X	X	X	X		X		
Pseudophryne raveni		X		X	X	X		X		
Pseudophyrne major		X		X	X	X		X		
Uperoleia fusca		X		X	X	X		X		
Litoria chloris	X				X	X		X		
Litoria gracilenta	X	X	X	X	X	X		X		
Litoria revelata	X		X		X	X		X		
Litoria wilcoxii		X	X	X	X	X	X			

Species	**Closed Forest (rainforest and wet sclerophyll forest communities)**	**Open Forest communities**	**Wet Tropics bioregion**	**Brigalow Belt North bioregion**	**Eungella. Central Mackay Coast bioregion**	**South Eastern Queensland bioregion**	**Stream (lotic)**	**Pool (lentic)**	**Direct Development**	**Conservation status (EPBC Act)**
Litoria caerulea		X	X	X	X	X		X		
Litoria fallax		X	X	X	X	X		X		
Litoria latopalmata		X	X	X	X	X		X		
Litoria rothii		X	X	X	X			X		
Litoria rubella		X	X	X	X			X		
Mixophyes carbinensis	X		X				X			
Mixophyes coggeri	X		X				X			
Mixophyes schevilli	X		X				X			
Mixophyes fleayi	X					X	X			
Mixophyes iteratus	X					X	X			
Philoria spp.	X					X			X	
Rheobatrachus silus	X					X	X		X	E
Taudactylus acutirostris	X		X				X			E
Taudactylus rheophilus	X		X				X			END
Assa darlingtoni	X					X			X	
Taudactylus diurnus	X					X	X			E
Taudactylus pleione	X					X	X			CE
Limnodynastes convexiusculus			X	X				X		
Pseudophyrne covacevichae			X							
Uperoleia altissima			X	X				X		
Limnodynastes fletcheri			X	X				X		

Species	Closed Forest (rainforest and wet sclerophyll forest communities)	Open Forest communities	Wet Tropics bioregion	Brigalow Belt North bioregion	Eungella, Central Mackay Coast bioregion	South Eastern Queensland bioregion	Stream (lotic)	Pool (lentic)	Direct Development	Conservation status (EPBC Act)
Limnodynastes salmini				X		X		X		
Crinia deserticola				X				X		
Crinia parinsignifera				X		X		X		
Crinia remota				X				X		
Crinia signifera				X		X		X		
Crinia tinnula						X		X		
Uperoleia lithomoda				X				X		
Litoria dayi	X		X				X			END
Litoria eucnemis	X		X				X			
Litoria jungguy	X		X				X			
Litoria lorica	X		X				X			CE
Litoria myola	X		X				X			END
Litoria nannotis	X		X				X			END
Litoria nyakalensis	X		X				X			CE
Litoria rheocola	X		X				X			END
Litoria serrata	X		X				X			
Litoria xanthomera	X		X					X		
Litoria brevipalmata	X					X		X		
Litoria dentata	X	X				X		X		
Litoria kroombitensis	X					X	X			
Litoria pearsoniana	X					X	X			

Species	**Closed Forest (rainforest and wet sclerophyll forest communities)**	**Open Forest communities**	**Wet Tropics bioregion**	**Brigalow Belt North bioregion**	**Eungella. Central Mackay Coast bioregion**	**South Eastern Queensland bioregion**	**Stream (lotic)**	**Pool (lentic)**	**Direct Development**	**Conservation status (EPBC Act)**
Litoria bicolor			X	X				X		
Litoria inermis			X	X			X			
Litoria infrafrenata			X	X				X		
Litoria microbelos			X					X		
Litoria nigrofrenata			X					X		
Litoria pallida			X					X		
Litoria nasuta			X	X		X		X		
Litoria olongburensis						X		X		
Litoria cooloolensis						X		X		
Cyclorana alboguttata				X				X		
Cyclorana brevicipes				X				X		
Cyclorana novaehollandiae				X				X		
Litoria aurea						X	X	X		
Litoria freycineti						X		X		
Litoria verreauxii						X		X		
Uperoleia laevigata						X		X		
Lechriodus fletcheri	X					X		X		
Hylarana daemeli	X		X				X			
Austrochaperina (4 spp.)	X		X						X	
Cophixalus (17 spp.)	X		X						X	

TABLE 2. Area of Occupancy (AOO) and Extent of Occupancy (EOO) for the three endemic anuran species found at Eungella, based on records in the *Atlas of Living Australia*. AOO is based on a 0.02 degree grid, and the EOO on the minimum convex polygon.

Species	**Number of Records**	**Area of Occupancy (sq. km.)**	**Extent of Occupancy (sq. km.)**
Rheobatrachus vitellinus	33	48	98
Rheobatrachus silus	127	108	753
Taudactylus eungellensis	579	28	405
Taudactylus liemi	144	16	115

Similarly, there are eight species of pelodryadid frogs in the WT, all of which belong to two species groups that show adaptations to stream dwelling. No members of these species groups occur south of the WT bioregion and, once again, the Burdekin Gap is regarded as a barrier that has prevented southward dispersal. Only one other closed forest pelodryadid occurs in the WT bioregion, *Litoria jungguy*, which is a close sibling of the southern stream frog *L. wilcoxii*.

Closed forest habitats in the SEQ bioregion have three myobatrachid genera (*Assa*, *Lechriodus* and *Philoria*) not found at Eungella, and which do not extend north across the St Lawrence Gap, and there are no populations of these at Kroombit Tops. Among the pelodryadid frogs, four closed forest species of *Litoria* (*L. brevipalmata*, *L. dentata*, *L. pearsoniana* and *L. kroombitensis*) do not cross the St Lawrence Gap. *Litoria pearsoniana* and *L. kroombitensis* are members of the '*L. phyllochroa* species group', which has five members in closed forest habitats of south and central eastern Australia. *Litoria kroombitensis* is the only endemic pelodryadid frog found in the isolated closed forest refugium at Kroombit Tops (northern SEQ bioregion), with the lower Mary-Burnett River basins separating it from *L. pearsoniana*. *Litoria dentata* does not occur north of the lower Mary-Burnett river basins in the SEQ bioregion, where it is most commonly found in wet sclerophyll forest. It is a member of the '*Litoria rubella* species group', and *L. rubella* is common in the open forests and woodlands of the CMC and BBN bioregions and extends farther to the north and west. It is a generalist, and its wide distribution in drier habitats indicates adaptations to these habitats in contrast to *L. dentata*. The remaining closed forest species, *Litoria brevipalmata*, is the only member of its species group, is distributed from mid-eastern NSW to SEQ, and breeds exclusively in ephemeral pools.

Last, there is a considerable diversity of species of myobatrachid and pelodryadid frogs that do not have records in the CMC bioregion (Table 1), but do occur in the open forest/savannah communities in the surrounding bioregions. Most of these species breed in still waters (permanent or ephemeral ponds and swamps). Several of these frogs (*Limnodynastes salmini*, *Crinia parinsignifera* and *C. signifera*) reach their northern limits in the BBN bioregion, but have extensive distributions to the south and west. Among the tree frogs, there are several species of *Litoria* (*L. fallax*, *L. inermis*, *L. latopalmata*, *L. caerulea*, *L. nasuta* and *L. rothii*) that are common in drier habitats of the coastal lowlands that have extensive distributions in eastern Australia; most do not have records in the closed forest habitats at Eungella (Table 1).

Several species found in the SEQ bioregion (*Crinia tinnula*, *Litoria cooloolensis*, *L. freycineti* and *L. olongburensis*) that do not extend north into the St Lawrence Gap are habitat specialists. These species are found in coastal sandy habitats known as the Wallum (wet heaths on sandy soils) (Coaldrake, 1962), that occur south of the St Lawrence Gap.

Several species of the pelodryadid genera *Cyclorana* occur in the drier and hotter open forest, woodland and grassland communities of the CMC, BBN, EU and BS bioregions, and traverse the Burdekin and St Lawrence Gaps. These 'burrowing' tree frogs do not enter closed forest communities.

DISCUSSION

To understand and interpret the evolutionary history of Australian amphibians, with particular reference to eastern Australia, the isolated closed forest refugium of Eungella represents an area of great importance. Eungella, along with other isolated closed forest refugia that are associated with upland areas of the Great Dividing Range, provides evidence of a long evolutionary relationship and adaptive radiation of the old endemic amphibian fauna whose ancestors were present in Australia from the time it was part of the ancient supercontinent of Gondwana, at least 32 Mya

(Crisp *et al.*, 2001; Byrne *et al.*, 2008; Byrne *et al.*, 2011). At Eungella, three old lineages that are basal in the branching tree of the Australian ground frogs occur and their distributions are extremely narrow.

Three endemic frog species (*Rheobatrachus vitellinus*, *Taudactylus eungellensis* and *T. liemi*) occur at Eungella, and isolated populations of five other species (*Adelotus brevis*, *Myxophyes fasciolatus*, *Uperoleia fusca*, *Litoria chloris* and *L. revelata*) are present. A measure of endemism that tallies species that are restricted to a particular area does not effectively account for the evolutionary depths of those species or their lineages. Diversity or evolutionary history is distributed unequally among taxa as well as between areas (Rosauer *et al.*, 2009), and the concepts of phylogenetic diversity and phylogenetic endemism have been defined to capture these important values (Rosauer *et al.*, 2009; Moritz & Faith, 1998; Faith *et al.*, 2004). Rosauer *et al.* (2009) defined phylogenetic endemism as the combination of phylogenetic depth and range-weighted species endemism, and used it to identify areas where a substantial component of phylogenetic diversity is restricted to small distributions. When these values of phylogenetic depth and small distribution are considered, the evolutionary history represented among the anuran fauna at Eungella takes on an important perspective. Three of the genera occurring at Eungella (*Mixophyes*, *Rheobatrachus* and *Taudactylus*) represent ancient lineages (Frost *et al.*, 2006; Read *et. al.*, 2001; Mahony *et al.*, 2006).

Phylogenetic studies have shown that *Rheobatrachus*, along with *Mixophyes*, forms the sister lineage to all other Australian myobatrachids (Frost *et al.*, 2006). Read *et al.* (2001) provided a phylogenetic study of the subfamily Myobatrachinae, without the inclusion of *Rheobatrachus* and *Mixophyes* as it was considered at the time, and they assumed monophyly of the group and used only *Limnodynastes* as a representative of the subfamily Limnodynastinae to root the tree. Their results provided strong evidence that *Taudactylus* was the sister lineage to all other members of the subfamily Myobatrachinae (=Myobatrachidae) as then considered (see Frost *et al.*, 2006 for a discussion). Although there remains uncertainty around the higher-level taxonomy and the most reliable phylogenetic reconstruction, there is no doubt of the ancient evolutionary history of the lineages of *Rheobatrachus*, *Taudactylus* and *Mixophyes*. On this basis, Eungella supports exceptionally high phylogenetic endemism, as represented by the long phylogenetic branches and extremely narrow distributions of *Rheobatrachus* and *Taudactylus*. Investigations of several anuran lineages have found that species endemism in the east coast, closed forest refugia tends to reflect deeper evolutionary processes and underestimates recent phylogeographic dynamics (Roseaur *et al.*, 2015).

Also important in considering the evolutionary history and biogeography of the Australian ground frogs and the information that comes from Eungella is which closed forest taxa do not occur there. Several genera of Limnodynastidae (*Philoria* and *Lechriodus*) and Myobatrachidae (*Assa*) do not occur there, but are found in closed forest of the SEQ biogregion. These taxa do not extend northwards across the St Lawrence Gap to the south of Eungella. Similarly, there are several taxa (Microhylidae and Ranidae) found in the closed forest refugia of the WT bioregion to the north of Eungella, which have not dispersed across the Burdekin Gap that separates Eungella from the WT bioregion. However, there is no myobatrachid genus found in the WT bioregion that does not occur at Eungella.

In addition to the high level of phylogenetic endemism, Eungella also supports high species richness of anurans, with over 21 species of frog recorded in the CMC bioregion. Several genera of closed forest frogs (*Rheobatrachus* and *Adelotus*), and several species (*Mixophyes fasciolatus*, *Litoria chloris* and *Uperoleia fusca*), reach their northern distributional limit at Eungella. The high level of species richness results from a combination of the endemic elements: a diversity of species that occur in the lowlands and that have more extensive distributions in the coastal zone, plus a small number of species whose adaptations are to savannah and semi-arid environments.

Many studies have investigated the historical biogeography and evolution of the biota of the cool and wet upland closed forest habitats of the eastern seaboard of Australia, and there is a general consensus on the role of refugia and barriers among them (Joseph *et al.*, 1995; Stuart-Fox *et al.*, 2001; Mahony *et al.*, 2006; Rosauer *et al.*, 2009, 2015). The closed forests form an archipelago of refugia dominated by rainforest communities (temperate, sub-tropical and tropical rainforests) surrounded by lowlands of hot and drier open forest dominated by sclerophyll communities (Crisp *et al.*, 2001). Eungella (the Clarke Range) in particular is considered an area of long-term mesic forest persistence (Stuart-Fox *et al.*, 2001). Closed forest habitats are restricted to upland areas usually associated with the great escarpment, and eastern uplands of the Great Dividing Range, and there is compelling evidence that these habitats are mostly due to an altitudinal (i.e. topographic) effect. However, the distance of the mountain ranges from the coast is also an important component since it is associated with rainfall patterns driven by maritime influences (Hampe & Jump, 2011). This latter orographic rainfall effect cannot be underestimated, and coastal fog commonly settles on the high peaks at Eungella in the late afternoon. Indeed, it is the origin of Eungella's Aboriginal name, 'mountains of the mist'. Understanding of the historical climate of eastern Australia, derived mostly from palynology and karst deposits, demonstrates a rapid and widespread change from extensive rainforest habitats to a much drier landscape dominated by woodland and savannah ecosystems since the late Pleistocene (Bryant & Krosch, 2016). Many of the refugia have apparently experienced relatively long climate stability, and they retain ancient lineages that do not occur in habitats outside the closed forests (Byrne *et al.*, 2011).

Eight major biogeographical disjunctions, termed barriers or gaps, for closed forest taxa were identified in eastern Australia by Bryant & Krosch (2016), based on evidence of common barriers that separated many wet forest adapted biota. Two of these barriers are significant with respect to Eungella, namely the Burdekin Gap to its north (Burdekin River Catchment, also referred to as the Bowen Basin) and the St Lawrence Gap (Fitzroy River Catchment) to its south, both of which are in the BBN bioregion that surrounds the MCC bioregion. Bryant & Krosch (2016) synthesised common phylogeographic patterns for a range of taxa, and provided inferred timing where studies had estimated age of separation using molecular genetic approaches. The outcome is that the Burdekin Gap has been a stronger barrier to movement of closed forest taxa than the St Lawrence Gap. The Burdekin Gap coincides with the northern extent of the 'Brigalow Belt North' bioregion, a large dry corridor that stretches from the southern boundary of both the Wet Tropics bioregion and what is considered the Australian Monsoonal Tropics, to the Bowen Basin in the south (Catullo & Keogh, 2014). Studies show that there is currently very little closed forest habitat within the putative bounds of the Burdekin Gap, providing limited opportunities for taxa to disperse across the barrier using smaller patches of suitable habitat as stepping stones (Bryant & Krosch, 2016).

The cool upland closed forests form refugia for those taxa that are unable to disperse across the hotter and drier barriers. These refugia provide a window to the past when the climate was wetter and cooler, and rainforest communities were more widespread (Byrne *et al.*, 2011). At that time, there must have been some interconnection among the current refugia, since the ancestors of the extant species must have been more widely distributed and able to disperse across what are now drier barriers. Isolation of populations in refugia is known to break gene flow among populations, potentially leading to speciation and, for some, taxa extinction (Moritz & Faith, 1998; Moritz *et al.*, 2005; Hampe & Jump, 2011). Amphibians that are adapted to closed forest habitats are one group for which drying and possibly warming of climate leads to population isolation in closed forest refugia, since their complex life history and physiology (Hillman, 2008) mean that most are reliant on a constant source of water. However, not all anurans have responded to these changes in the same way, which most likely reflects differences in physiological tolerances and ecology. At Eungella, there are several anurans that are endemic, other species with isolated populations but which are not endemic, and still others that have continuous distributions with the surrounding drier habitats. Typically, the species that occur in the drier forest habitats are adapted to breed in permanent and ephemeral wetlands, whereas those in the closed forest are reliant on stream habitats (Table 1). One stream-breeding frog, *Litoria wilcoxii*, traverses the St Lawrence and Burdekin Gaps. This frog occurs in most eastern-flowing catchments and in the upper reaches of western-flowing streams of the Great Dividing Range from the Sydney Basin bioregion to the WT bioregion (see Meyer *et al.*, this volume). It occurs in streams across the altitude range at Eungella, and is most abundant in the wet forests that fringe the dense rainforest. Interestingly, in the WT a sister taxon, *Litoria jungguy*, is found almost exclusively in the closed forest, and *L. wilcoxii* occurs in the adjacent drier and open forests. Biogeographic studies have demonstrated a similar pattern for many taxa, with refugia harbouring species of varying dispersal abilities and ecologies, and with varying capacity to move across zones of otherwise unsuitable habitat (Byrne *et al.*, 2011).

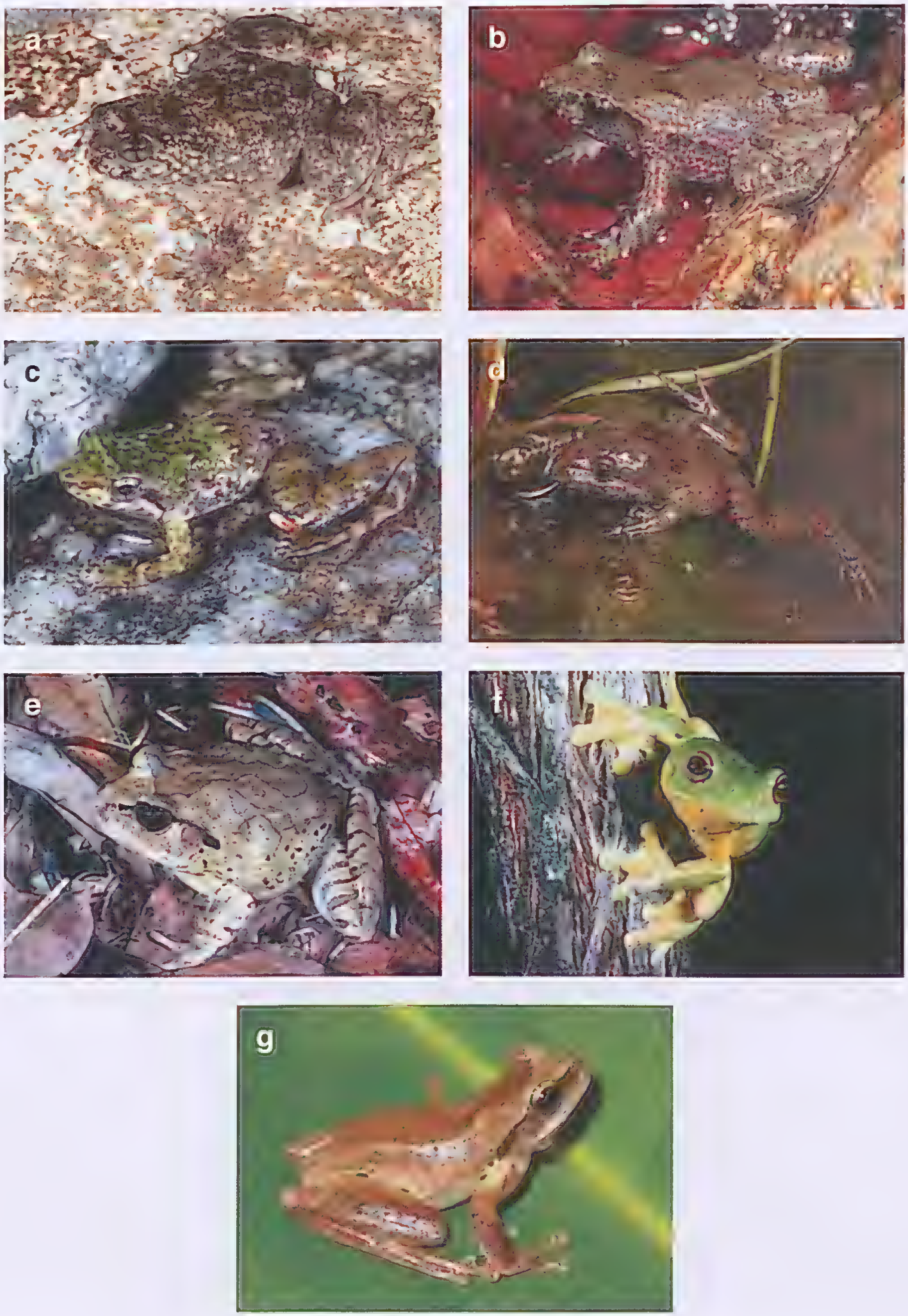
Estimates of the age of the divergence among amphibian taxa that occur in the refugia are of considerable importance to understanding the evolutionary history of these ecosystems. However, there is limited information available on the age of separation of two important taxa, *Rheobatrachus* and *Taudactylus*. Divergences calculated from intra-generic comparisons reveal an inferred age from the late Miocene to the late Pleistocene (12–7 Mya) for species of *Mixophyes* (Mahony *et al*., 2006), and mid-Miocene to Oligocene (23–10 Mya) among species of *Uperoleia* (Catullo & Keogh, 2014). These intra-generic speciation events logically post-date the differentiation of the generic lineages, and differentiation of the older lineages, such as *Rheobatrachus* and *Taudactylus*, must predate these time estimates. Apart from *R. vitellinus* at Eungella, the only other species of *Rheobatrachus* (*R. silus*) occurred in the closed forests of the Conondale and Blackall Ranges (SEQ bioregion), and both species have very similar derived reproductive biology and morphological adaptations to stream habitats (Liem, 1973). The distribution of *Taudactylus* is more widespread among the refugia, with one species found in the Dawes Range (Kroombit Tops) to the south-east of Eungella, another further south in the Conondale, Blackall and D'Aguilar Ranges (all in the SEQ bioregion), and two species to the north in the rainforests of the WT bioregion. Kroombit Tops is isolated from Eungella by the St Lawrence Gap and represents an important closed forest refugium between those at Eungella and those to the south. Kroombit Tops is isolated from the other closed forests of the SEQ bioregion by the lower Mary-Burnett River basins. This barrier is not considered by Bryant & Krosch (2016) as being significant for birds or flora, but it appears to have been significant for anurans.

Further evidence of the antiquity of *Rheobatrachus* and *Taudactylus* come from their life history and adaptations. *Rheobatrachus* is Australia's only truly aquatic frog, apparently spending its whole life in water and not venturing for any extended period onto land during the adult stage (Mahony *et al*., 1984; Liem, 1973). Evidence can be seen in the convergence of external morphology with other unrelated aquatic anurans such as xenopipids (flattening of the body, protuberant eyes, well-developed muscular hind limbs with extensively webbed toes, the occurrence of lateral line organs and production of copious epidermal mucous secretions). All *Taudactylus* species have a derived reproductive biology in which a relatively small number (average 30) of large unpigmented eggs are laid beneath rock or debris in streams or rocky crevices associated with stream habitats.

In contrast to the ground frogs (Myobatrachidae and Limnodynastidae) which have endemic species and isolated populations from ancient lineages at Eungella, there is no endemic species of tree frog (Pelodryadidae) at Eungella. Two species (*Litoria chloris* and *L. revelata*) have disjunct populations at Eungella and, in each case, they are examples of species that are more widely distributed to the south of the St Lawrence Gap. A sister species of *L. chloris*, *L. xanthomera*, and an isolated population of *L. revelata* occur in the closed forests of the WT bioregion. In these cases, the Burdekin Gap has provided some level of isolation but apparently has not prevented the dispersal of *L. revelata* across the Gap. It is assumed that the dispersal is northward on the basis that this species is more widely distributed in southern bioregions, but this has not been tested by a robust phylogenetic analysis. Perhaps more telling of the strength of the Burdekin Gap as a barrier is the absence of any species of the WT stream-adapted clade of tree frogs ('*Litoria nannotis* species group') at Eungella. In this case, it is assumed that the Burdekin Gap is a barrier to southward dispersal of this group which has several sibling species in closed forest of the WT bioregion.

Evidence of closer historical connections between the closed forest refugium of Eungella and those to the south (in the SEQ bioregion), rather than those to the north in the WT bioregion, is indicated by taxa that have isolated populations at Eungella and that occur in the southern but not the northern bioregion. This indicates that for anurans, the Burdekin Gap has been important in both limiting southward-colonising and northward-colonising mesic forest species, and promoting divergence among populations of species that span the barrier (Bryant & Krosch, 2016). *Adelotus brevis*, *M. fasciolatus*, *Upereoleia fusca* and *L. chloris* have disjunct populations at Eungella that are conspecific with populations to the south but not to the north of Eungella (Table 1). All of these frogs, with the exception of *Uperoleia fusca*, are considered to be associated with closed forest communities. *Uperoleia fusca* is widely distributed in open and closed forest habitats to the south of Eungella, but apparently not in the St Lawrence Gap. In contrast, there is a stronger differentiation with northern closed forest species of the WT bioregion. Five species of *Litoria* tree frogs, three species of *Mixophyes* and two species of *Taudactylus* do not extend south of the WT bioregion. In addition, there are no members of the family Microhylidae (14 species in the WT bioregion), or Ranidae (*Hylarana daemeli*) that occur south of the WT bioregion. Biogeographic and phylogenetic studies are in strong agreement that the Australian members of these two families have dispersed into Australia from the north and that they are not of Gondwanan origin (Tyler, 1979).

FIGURE 2. Three of the endemic closed forest anurans of Eungella, a) *Rheobatrachus vitellinus*, b) *Taudactylus liemi*, and c) *Taudactylus eungellensis*; and species that have disjunct populations at Eungella, d) *Adelotus brevis*, e) *Mixophyes fasciolatus*, f) *Litoria chloris*, and g) *Litoria revelata*.



Rosauer *et al.* (2015) found that regions of high species endemism that identify hotspots of highly restricted, isolated and independently evolving populations are central to identifying taxa and areas of conservation priority. The closed forest habitats of Eungella within the CMC bioregion support a disproportionate amount of restricted evolutionary diversity and provide a prime example of this priority. The occurrence of three endemic species from two basal lineages, isolated populations of more widespread taxa, and high species richness demonstrates its significance as a conservation hotspot. Further research is required to understand more fully the ages of divergence and antiquity of the endemic anuran fauna of Eungella and the other closed forest refugia of eastern Australia.

ACKNOWLEDGEMENTS

Special thanks to Olivier Rey-Lescure who produced the map that is Figure 1, and to Stephen Mahony for the photographs of *T. liemi* and *T. eungellensis*. Harry Hines gave important advice on the distribution of several species of frogs in the bioregions surrounding Eungella.

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AN UPDATE ON THE STATUS OF WET FOREST STREAM-DWELLING FROGS OF THE EUNGELLA REGION

MEYER, E. A.[1], HINES, H. B.[2], CLARKE, J. M.[3] & HOSKIN, C. J.[4]

Eungella's wet forests are home to a number of stream-breeding frogs including three species endemic to the Eungella region: the Eungella dayfrog (*Taudactylus eungellensis*), Eungella tinkerfrog (*T. liemi*), and northern gastric brooding frog (*Rheobatrachus vitellinus*). During the mid-1980s, *T. eungellensis* and *R. vitellinus* suffered dramatic population declines attributable to amphibian chytridiomycosis, a disease caused by the amphibian chytrid fungus (*Batrachochytrium dendrobatidis* or Bd). While surveys in the late 1980s failed to locate *T. eungellensis* or *R. vitellinus*, populations of the former were located on a handful of streams surveyed by researchers in the mid-to-late 1990s. Between January 2000 and November 2015, additional surveys targeting these and other wet forest frog species were conducted at 114 sites within Eungella National Park and adjoining areas of State Forest. During these surveys, we located *T. eungellensis* at many more sites than surveys in the 1990s. Abundances of *T. eungellensis* at these sites were typically low, however, and well below abundance levels prior to declines in the mid-1980s. As with surveys in the 1990s, *T. eungellensis* was scarce at high-elevation sites above 600 metres altitude. Numbers of this species do not appear to have increased significantly since the mid-1990s, suggesting recovery of *T. eungellensis* populations is occurring slowly, at best. In contrast with *T. eungellensis*, *T. liemi* was frequently recorded at high-elevation sites, albeit at low densities. As with previous surveys, surveys during 2000–2015 were unsuccessful in locating *R. vitellinus*. Further frog surveys and monitoring (including disease surveillance) are needed to better assess the status of stream frogs at Eungella, and to understand the influence of Bd on the abundance and distribution of threatened stream-dwelling frogs at Eungella.

Keywords: Eungella, frogs, conservation status

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INTRODUCTION

The wet forests of Eungella are home to a number of stream-dwelling frogs including three species endemic to the Eungella region: the northern gastric brooding frog (*Rheobatrachus vitellinus*), Eungella dayfrog (*Taudactylus eungellensis*), and Eungella tinkerfrog (*T. liemi*). Once common in areas of suitable habitat, *R. vitellinus* and *T. eungellensis* suffered dramatic population declines in the mid-1980s, and neither species could be located during surveys in the late 1980s and early 1990s (McDonald, 1990). Numbers of another more widely distributed species, the tusked frog (*Adelotus brevis*), may also have declined at sites north of Eungella township in the mid-1980s. No declines were noted in *T. liemi* or any other stream-dwelling frog species known from the Eungella region at this time (McDonald, 1990); however, data on these species are sparse. More recently, Anstis (2013) reported a possible decline in *T. liemi* numbers at Eungella, but provided little in the way of evidence to support this claim.

The sudden population declines at Eungella during the 1980s are likely attributable to amphibian chytridiomycosis, a disease caused by the amphibian chytrid fungus (*Batrachochytrium dendrobatidis* or Bd), which has also been implicated in declines affecting other stream-breeding species in south-eastern Queensland and the Wet Tropics region of northern Queensland during the late 1970s and late 1980s/early 1990s (Richards *et al*., 1993; Retallick *et al*., 2004; Scheele *et al*., 2017; Berger, 2000; Murray *et al*., 2010). This fungus and disease were only described in the late 1990s and were unknown at the time that declines affecting *T. eungellensis* and *R. vitellinus* took place.

Before its disappearance in the mid-1980s, *R. vitellinus* was known from rocky rainforest streams above 405 m altitude (Figure 7C) with animals commonly encountered in shallow water amongst rocks in riffle zones and around cascades (McDonald, 1990). At this time, *R. vitellinus* was known from first, second and third order streams within the catchments of Finch Hatton, Urannah, Cattle and Owens Creeks (McDonald, 1990; Figures 1A and 2). *Taudactylus eungellensis* was more broadly distributed at Eungella, and while present on some of the same streams inhabited by *R. vitellinus*, was more commonly encountered on larger (third, fourth and fifth order) streams, including streams at lower elevation (below 405 m altitude) (McDonald, 1990). Unlike *R. vitellinus*, *T. eungellensis* was also present in wet forest areas south of the township of Eungella, within the Broken River and Cattle Creek (South Branch) catchments (McDonald, 1990; Liem & Hosmer, 1973; Figures 1B and 2). According to McDonald (1990), both species were common across their range until January 1985, when declines were first noted at lower-altitude sites (around 400–500 m altitude). Thereafter, numbers of *T. eungellensis* and *R. vitellinus* declined dramatically, and neither species could be located after 1986 despite repeated surveys throughout the late 1980s (McDonald, 1990).

In 1992, six years after *T. eungellensis* was last sighted in the wild, a single subadult animal was seen and photographed on Boulder Creek in the east of Eungella National Park (Couper, 1992; P. Couper, Queensland Museum, *pers. comm.*). Surveys led by James Cook University researchers Jean-Marc Hero and Richard Retallick the following year located *T. eungellensis* on a small number of streams in the south and east of Eungella National Park; however, no *R. vitellinus* were seen or heard at this time (McNellie & Hero, 1994). Subsequent surveys and monitoring conducted by Retallick during the mid-to-late 1990s yielded additional records of *T. eungellensis*, as well as data on the abundance and population trends of *T. eungellensis* and other stream-dwelling frogs in the south and east of the Clarke Range (R. Retallick, *pers. comm.*, unpublished report). Despite targeted surveys, no *R. vitellinus* were located at this time either (McDonald & Alford, 1999; Northern Queensland Threatened Frogs Recovery Team, 2001). A more recent unsuccessful survey targeting *R. vitellinus* was mentioned by Moore (2014), but no details of areas searched or observations of other frog species were provided.

In this paper, we present data from coordinated surveys and monitoring targeting *T. eungellensis*, *T. liemi* and *R. vitellinus* carried out by Queensland Parks and Wildlife Service staff and volunteers (including the authors) through 2000–2006, and subsequent surveys led by Conrad Hoskin. This includes survey results from sites in remote and difficult-to-access parts of Eungella National Park not previously surveyed for frogs, as well as resurveys of historical sites for *R. vitellinus* and *T. eungellensis*. Surveys targeting these species also yielded data on other wet forest and stream-associated frogs (*A. brevis*, *Litoria revelata*, *Litoria chloris*, *Litoria wilcoxii/jungguy*, *Mixophyes fasciolatus*), some of which are highly localised in the Eungella region and may also have been impacted by the emergence of chytridiomycosis, albeit to a lesser extent than *R. vitellinus* or *T. eungellensis*. Collectively, these data provide the most comprehensive and up-to-date assessment of the status of wet forest stream-dwelling frogs at Eungella currently available.

MATERIALS AND METHODS

Nomenclature and Terminology

The nomenclature in this paper follows that used in the Queensland Government's WildNet database. Although genetically distinct, the northern and eastern stony creek frog (*Litoria jungguy* and *L. wilcoxii*, respectively) are very similar in appearance and difficult to separate in the field (Donnellan & Mahony, 2004). Records of these species have therefore been combined. In this paper, the term 'site' refers to a section of stream between confluences as mapped on the 1:50,000 topographic map sheets available at the time surveys were undertaken.

Data Sources

The data presented in this paper are from two main sources: (1) surveys and standardised monitoring coordinated by Queensland Parks and Wildlife Service (QPWS) through 2000–2006 (comprising the 'QPWS dataset'); and (2) surveys undertaken by Conrad Hoskin and colleagues through 2009–2015 (comprising the 'Hoskin dataset'). Details of these surveys and associated datasets are provided below, while the location of survey and monitoring sites is shown in Figure 2A.

QPWS Surveys and Data

The QPWS dataset comprises data from annual surveys and standardised monitoring undertaken by QPWS staff and trained volunteers from January 2000 through to December 2006 (JC, EM and/or HH were the key personnel involved in planning and implementing these surveys). Annual surveys run by QPWS were undertaken during the 1999–2000, 2000–2001, 2001–2002, 2003–2004, and 2005–2006 wet seasons (see Table 1 for details regarding the timing of surveys). During these surveys, wet forest streams of the Clarke Range, principally within Eungella National Park and also nearby areas of State Forest (including Crediton and Cathu State Forest), were surveyed for frogs and tadpoles by teams of 3–4 observers. In most cases, streams were surveyed by day and night (in the afternoon and early evening), with observers using headlamps and dipnets to locate frogs and tadpoles along and adjacent to streams.

During annual surveys, QPWS staff and volunteers surveyed 84 stream sites within the catchments of Broken River, Finch Hatton, Cattle (North and South Branches), upper Urannah, Boulder, upper St Helens, Rawsons, Amelia, Massey, Quandong, Cathay and Tree Fern Creeks (Figure 2). This included historical sites that *T. eungellensis* and *R. vitellinus* were known from prior to declines in the 1980s, sites surveyed by Retallick and Hero in the early-to-mid 1990s, and a number of sites not previously surveyed for frogs. A significant proportion (~75%) of these were surveyed on multiple occasions through 2000–2006. In between annual surveys, QPWS staff and volunteers undertook additional censuses at a number of monitoring transects established by Retallick and Hero (Retallick *et al.*, 1997, unpublished), including sites on Rawsons, Tree Fern, Finch Hatton, and Mt William and Mt David Creeks (the latter two in the upper Cattle Creek North Branch catchment) (Figure 2; Table 2). Details regarding the timing of these additional censuses are provided in Table 1.

For each diurnal and nocturnal survey, the following information was recorded on a pro forma: (1) the number of each species observed; (2) the age/life stage and reproductive condition of animals observed; (3) how animals were observed (i.e. whether animals were heard, seen or handled/captured); (4) the presence of sick, moribund or dead animals; (5) stream flow and water quality; (6) the nature and extent of any pig or fire damage; (7) the date, start and end times for each survey; (8) the length of stream surveyed; (9) weather conditions during and preceding surveys; (10) the names of the observers; and (11) site and transect location.

FIGURE 1. Map of the Eungella area showing the historical distribution of (A) *Rheobatrachus vitellinus* and (B) *Taudactylus eungellensis* at sites surveyed by McDonald (1990), prior to catastrophic declines in the mid-1980s. Presence sites represented by closed circles (●), absence sites by open circles (○). After McDonald (1990). Refer Figure 2 for further details of the study area.

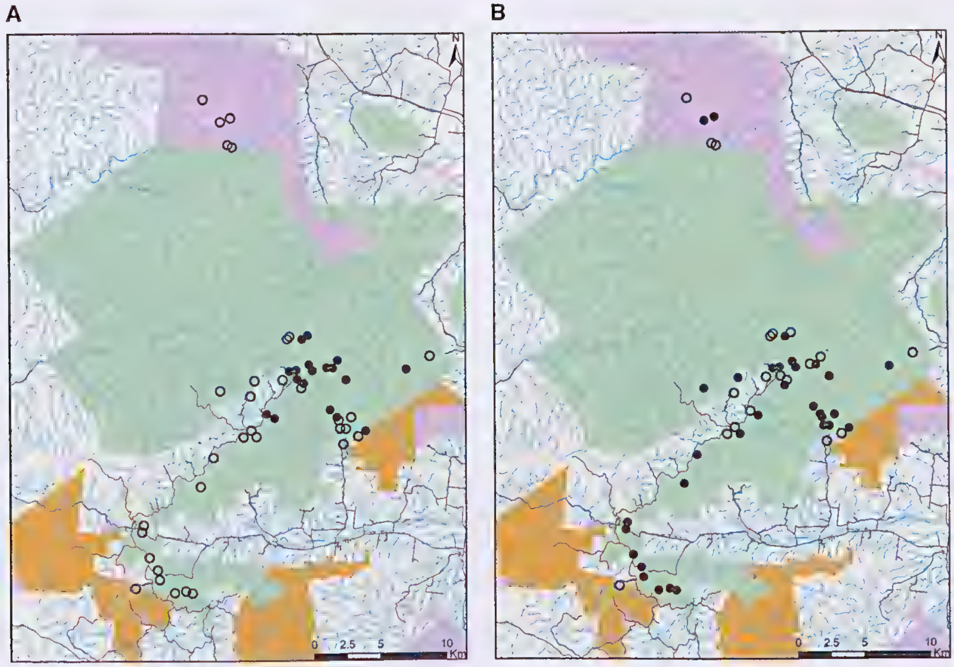
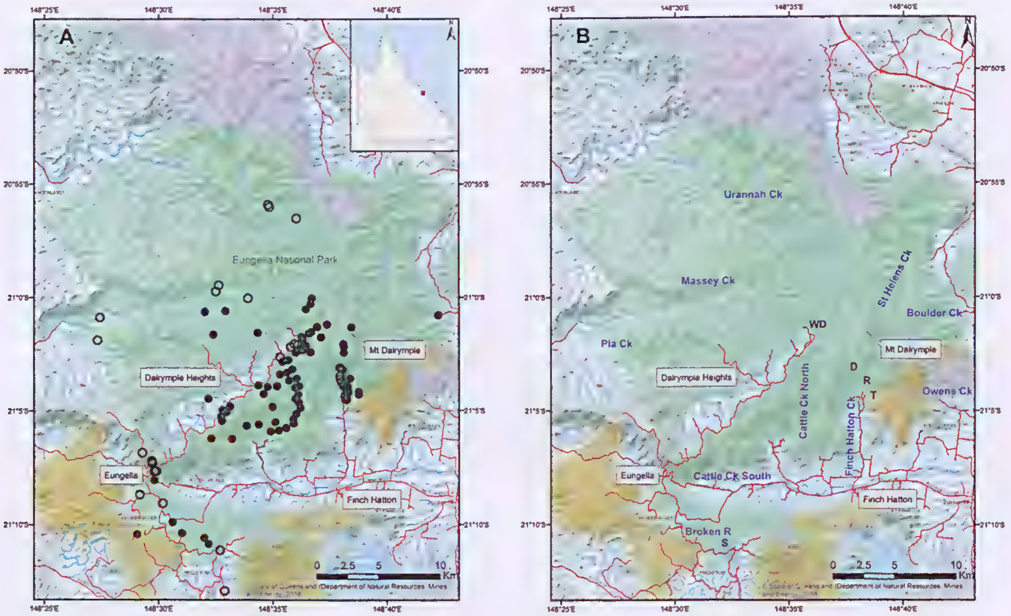


FIGURE 2. Maps of the Eungella area showing: (A) the location of survey sites included in QPWS and Hoskin datasets from 2000–2015, with QPWS sites represented by closed circles (•) and Hoskin sites by open circles (o); (B) major creek catchments and the location of QPWS monitoring transects (WD = Mount William and Mount David Creeks, D = Dooloomai Falls, R = Rawsons Creek, T = Tree Fern Creek and S = Sunrise Creek). In these figures, Eungella National Park is shaded light green, forest reserves brown and state forests pink. Major drainage lines are shown in blue and roads in red. The townships of Eungella and Finch Hatton are labelled, as well as the locality of Dalrymple Heights and Mount Dalrymple, the highest point in the study area at 1260 metres altitude. Base map sourced from http://qtopo.dnrm.qld.gov.au



In addition to records from the aforementioned surveys, the QPWS dataset includes additional opportunistic observations through 2000–2009 from EM and members of the Mackay Bushwalkers' Club (confirmed by HH and EM from field notes and/or photographs).

Hoskin Surveys and Data

The Hoskin dataset includes georeferenced data from a number of smaller surveys led by CH from 2009 to 2015 (see Table 1 for details). While some of the sites surveyed by CH overlap with sites surveyed by QPWS (e.g. sites in lower Finch Hatton Creek, and headwater streams of Cattle Creek North Branch), the majority were on streams not surveyed by QPWS through 2000–2006. This includes a number of remote and difficult-to-access streams at low-to-mid elevation in the lower Pla Creek and Massey Creek, and mid/upper Urannah Creek catchments, most of which appear not to have been surveyed for frogs previously. For the most part, CH recorded only the frog species present and relative abundance of species present at each survey site.

Disease Management and Surveillance

As discussed earlier, frog population declines at Eungella during the mid-1980s are likely attributable to the emergence of amphibian chytridiomycosis, a disease implicated in the decline and disappearance of stream frogs in other parts of Queensland. To understand the current impact of this disease on frog species at Eungella, QPWS survey teams were asked to keep a record of any sick and/or dead animals encountered during surveys. A subset of sick/moribund animals were swabbed and tested for amphibian chytrid fungus using techniques described in Murray *et al.* (2010). Apparently healthy frogs and tadpoles were also tested for amphibian chytrid fungus at a handful of survey sites.

TABLE 1. Summary of survey effort showing the timing and location of stream frog surveys coordinated by QPWS and C. Hoskin from 2000 to 2015, including the number of sites surveyed in each creek catchment.

Year	Month	Dataset	No. of sites	Amelia Creek	Bee Creek	Boulder Creek	Broken River	Cathay Creek	Cattle Creek North	Cattle Creek South	Endeavour Creek	Finch Hatton Creek	Hazelwood Creek	Massey Creek	Pla Creek	Quandong Creek	Rawsons Creek	St Helens Creek	Tree Fern Creek	Urannah Creek
2000	10	QPWS	3									2					1			
2000	12	QPWS	21			1	4	1	4	1	1	3	1			2	2		1	
2001	5	QPWS	5							1		2					2			
2001	11	QPWS	30	1		1	3		12	1		6		2			2	1	1	
2002	9	QPWS	5									2					2		1	
2002	11	QPWS	13				1		7			3					1		1	
2002	12	QPWS	21				1		12			1		2			2			3
2003	5	QPWS	2									2								
2003	9	QPWS	1														1			
2004	1	QPWS	23				3		12	1		2					3		2	
2004	4	QPWS	4									2					1		1	
2004	7	QPWS	4									2					1		1	
2004	10	QPWS	4						1			1					1		1	
2005	2	QPWS	6						1			2					2		1	
2005	5	QPWS	5						1			2					2			
2005	9	QPWS	3									2					1			
2005	10	QPWS	5						1			1		1			2			
2006	1	QPWS	4									2					1		1	
2006	2	QPWS	5						2			1					1		1	
2006	9	QPWS	1														1			
2006	10	QPWS	2									2								
2006	12	QPWS	30				2		21	1		2		1			2		1	
2008	2	QPWS	1														1			
2009	9	Hoskin	2											1	1					
2010	12	QPWS	1						1											
2012	2	QPWS	1						1											
2012	10	Hoskin	10		4		2		1			2		1						
2014	3	Hoskin	5				3		1			1								
2015	11	Hoskin	22				1		4	3		7		3			1			3

TABLE 2. Frog monitoring sites surveyed by QPWS staff and trained volunteers from 2000 through to 2006.

Location	**Altitude (m)**	**Distance (m)**
Rawsons Creek	330	200
Dooloomai Falls (Right-hand Side), Finch Hatton Creek catchment	550	200
Dooloomai Falls (Left-hand Side), Finch Hatton Creek catchment	550	200
Mt David Creek: Upper tributary of Cattle Creek (North Branch) draining from western slopes of Mt David	940	700
Mt William Creek: Upper tributary of Cattle Creek (North Branch) on southern slopes of Mt William	980	400
Tree Fern Creek	230	200
Sunrise Creek: Tributary of Broken River approximately 3.5 km east-south-east of the QPWS base at Broken River	790	200

Because of the threat posed by amphibian chytridiomycosis and other diseases, hygiene protocols were adopted to reduce the risk of spreading pathogens to and from the Eungella region, as well as amongst survey sites. To reduce the risk of pathogen spread between sites, footwear and dipnets were cleaned and disinfected when moving between sub-catchments. In order to reduce the risk of disease transmission between animals, frogs and tadpoles were also handled using separate disposable gloves and freezer bags.

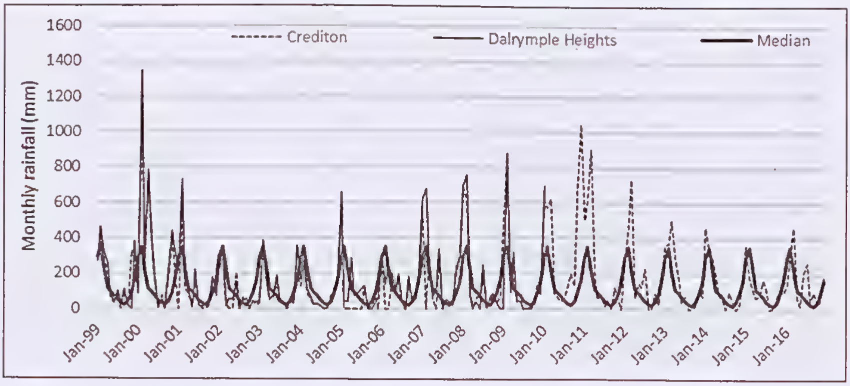
Climatic Conditions During Surveys

Monthly rainfall data for the Eungella area over the period in which surveys were undertaken are presented in Figure 3. The data in this figure show significant variation in wet season rainfall from 1999 to 2016, with above-median falls during the 1999–2000 and 2000–2001 wet seasons and below-median rainfall during subsequent wet seasons up until, and including, the 2005–2006 wet season. Rainfall totals for subsequent wet seasons were above or well above median up until 2013–2014, after which wet season rainfall was at median or below-median levels (Figure 3). While surveys in the very early 2000s coincided with above-median wet season rainfall, most of the surveys discussed in this paper were conducted in wet seasons with below-median rainfall.

Data Collation and Analysis

The QPWS dataset was managed using a Microsoft Access database. HH and EM vetted the data for suspect records (where the identification of frogs or tadpoles appeared doubtful and could not be verified).

FIGURE 3. Monthly rainfall totals for Crediton (south of Eungella township) and Dalrymple Heights weather stations from January 1999 to December 2016 (sourced from Bureau of Meteorology website http://www.bom.gov.au/climate/data/index.shtml accessed 15 July 2018). Median rainfall figures are based on data collected at Crediton over the period 1953–2018.



Presence records were used to generate distribution maps for each of the wet forest species encountered, as well as the introduced cane toad *Rhinella marina*, and to investigate altitudinal variation in site occupancy. Count data were also used to investigate altitudinal variation in frog abundance at presence sites. To account for variation in transect length, counts of post-metamorphic (adult and subadult) frogs recorded during surveys were standardised to 100 m. We used Microsoft Excel to plot maximum standardised counts for each site against altitude, and undertook regression analyses to investigate the relationship between frog abundance and altitude for all rainforest species encountered during surveys, except the whirring tree frog (*Litoria revelata*), which was only recorded at three sites between 930 and 980 m altitude. For the purposes of this analysis, site altitude was inferred from topographic maps using the approximate centre point of each site.

Long-term trends in the abundance of *T. eungellensis* and *T. liemi* at monitoring transects through 2000–2006 were investigated by plotting raw count data from standardised surveys against time and conducting regression analyses on these data.

RESULTS

Fifteen frog species were recorded on streams surveyed by QPWS and CH from 2000 to 2015. Table 3 summarises the number, altitudinal distribution and proportion of survey sites occupied by each species. More detailed information on the distribution and abundance of frog species recorded during surveys is provided below.

Northern Gastric Brooding Frog (Rheobatrachus vitellinus)

Despite searches of historical sites and numerous other rainforest streams above 400 m altitude, no *R. vitellinus* were recorded on any of the 114 sites surveyed through 2000–2015.

TABLE 3. Altitudinal distribution of frog species recorded during the current survey (QPWS and Hoskin datasets combined), 2000–2015.

			Site occupancy (proportion of survey sites where species recorded)			
Species	**Number of presence sites**	**Altitudinal range (m)**	**<350 m altitude (n=28)**	**350–600 m altitude (n=20)**	**601–850 m altitude (n=37)**	**>850 m altitude (n=29)**
Adelotus brevis	19	230–940	0.07	0.25	0.24	0.10
Limnodynastes peronii	9	230–980	0.11	0.00	0.14	0.03
Limnodynastes terraereginae	1	680	0.00	0.00	0.03	0.00
Litoria chloris	45	130–1020	0.29	0.45	0.41	0.45
Litoria fallax	4	220–980	0.04	0.00	0.00	0.10
Litoria gracilenta	2	680–790	0.00	0.00	0.05	0.00
Litoria inermis	1	130	0.04	0.00	0.00	0.00
Litoria latopalmata	1	980	0.00	0.00	0.00	0.03
Litoria wilcoxii/jungguy	60	130–980	0.61	0.75	0.54	0.28
Litoria revelata	4	930–980	0.00	0.00	0.00	0.14
Mixophyes fasciolatus	38	130–1000	0.18	0.35	0.38	0.41
Taudactylus eungellensis	32	190–1050	0.32	0.50	0.19	0.21
Taudactylus liemi	63	230–1050	0.25	0.45	0.65	0.79
Uperoleia fusca	2	880–940	0.00	0.00	0.00	0.07
Rhinella marina	21	130–790	0.39	0.30	0.11	0.00

Eungella Dayfrog (Taudactylus eungellensis)

During our surveys, we recorded *T. eungellensis* at 32 sites across five catchments, including Finch Hatton, Rawsons, Cattle (North Branch), Tree Fern and upper Urannah Creeks (Figure 4A). Sites with *T. eungellensis* ranged in altitude from 190 m to 1050 m, with the majority of presence sites below 700 m altitude. Site occupancy was highest below 600 m altitude, with *T. eungellensis* present at 50% of sites surveyed between 350–600 m altitude (Table 3).

During QPWS surveys, the abundance of *T. eungellensis* at presence sites was generally low, with numbers of post-metamorphic *T. eungellensis* rarely exceeding 10 animals per 100 m of stream transect. Counts of post-metamorphic *T. eungellensis* were generally higher below 700 m altitude, with the highest abundance (60 per 100 m of stream transect) recorded on Rawsons Creek, at 330 m altitude (Figure 5). In contrast with sites below 700 m altitude, counts of *T. eungellensis* at sites above 700 m altitude were consistently low, with no more than three animals recorded per 100 m of stream transect (Figure 5). Qualitative abundance data from surveys undertaken by Hoskin are broadly consistent with those from QPWS surveys, with *T. eungellensis* occurring at higher densities on lower elevation streams (<600 m altitude) compared with streams at higher elevation.

Summary statistics of *T. eungellensis* counts from QPWS monitoring transects over the period 2000–2006 are provided in Table 4. Counts at monitoring transects varied considerably between censuses and there was no clear or consistent trend in *T. eungellensis* numbers during this period, other than an apparent increase at Dooloomai Falls (Figure 6). On average, counts of *T. eungellensis* at monitoring transects were higher during diurnal surveys than nocturnal surveys (Table 4).

During our surveys, *T. eungellensis* were mostly recorded from larger, more open streams strewn with large rocks and boulders (Figure 7A). During diurnal surveys, adult and subadult *T. eungellensis* were mostly seen resting on wet rocks and boulders near areas of cascading water (Figure 7B). However, at night, animals were also observed sitting out on low vegetation (palm seedlings, sapling trees and fallen palm fronds) beside streams. Tadpoles of *T. eungellensis* were mainly recorded from deeper pools with slow-flowing water.

Only a small number of moribund/dead *T. eungellensis* were located during surveys, including two adult animals at Rawsons Creek (at 330 m altitude), one at Tree Fern Creek (at 230 m altitude) and one near Mt David Creek in the upper Cattle Creek North Branch catchment (at 1050 m altitude). Sick/moribund *T. eungellensis* were found sitting out in exposed situations (e.g. on bare rock) in various states of decomposition. One of the animals from Rawsons Creek was confirmed as being infected with chytridiomycosis (Murray *et al*., 2010).

Eungella Tinkerfrog (Taudactylus liemi)

During our surveys, *Taudactylus liemi* was recorded at 63 sites across 11 creek catchments, including Broken River, Amelia, Cattle (North and South Branches), Endeavour, Finch Hatton, Massey, Rawsons, St Helens, Tree Fern, and Urannah Creeks (Figure 4B). Sites where *T. liemi* was recorded ranged in altitude from 230 m to 1050 m above sea level. In contrast with *T. eungellensis*, *T. liemi* was more commonly encountered on streams above 600 m altitude than streams below 600 m, with *T. liemi* recorded at 65% of survey sites between 600 m and 850 m altitude (Table 3). The proportion of sites occupied by this species was even higher above 850 m altitude, where *T. liemi* was present at almost 80% of sites surveyed.

TABLE 4. Summary statistics and the results of linear regression analyses for count data from surveys undertaken at QPWS *T. eungellensis* monitoring transects from 2000 through to 2006. Regression analyses returning a non-significant result ($p > 0.05$) are denoted by the letters 'N.S.'. These data are based on counts of post-metamorphic animals from standardised censuses.

Site	Maximum count	Median count	Mean diurnal count (mean ± s.e.m.)	Mean nocturnal count (mean ± s.e.m.)	Results of regression analysis	Number of standardised surveys (diurnal/nocturnal)
Rawsons Creek	121	62.5	70.5 ± 6.00	45.36 ± 7.87	N.S.	44 (22/22)
Dooloomai Falls (LHS)	12	2	3.33 ± 1.02	1.93 ± 0.48	$p < 0.05$	30 (15/15)
Dooloomai Falls (RHS)	2	0	0.33 ± 0.19	0.11 ± 0.11	N.S.	21 (12/9)
Tree Fern Creek	11	1	2.38 ± 0.97	2.00 ± 1.20	N.S.	15 (8/7)
Mt William Creek	0	0	0	0	N.S.	20 (11/9)
Mt David Creek	1	0	0.0 ± 0.0	0.33 ± 0.33	N.S.	7 (4/3)

FIGURE 4. Distribution of frog species recorded during surveys from 2000 to 2015: (A) *T. eungellensis*; (B) *T. liemi*; (C) *A. brevis*; and (D) *L. chloris*. Presence sites represented by closed circles (●), absence sites represented by open circles (○). Refer to Figure 2 for a description of the features of the base map.

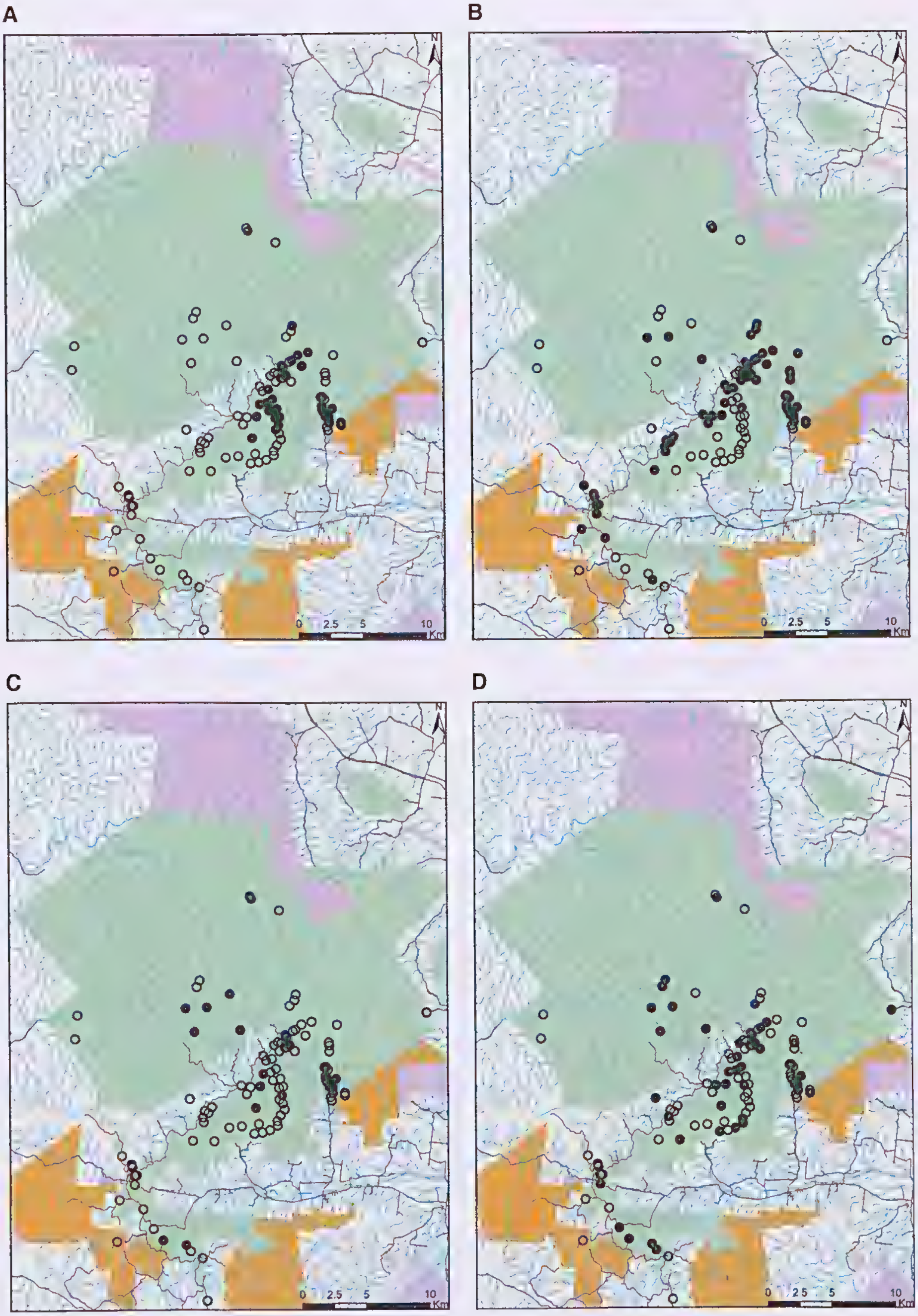
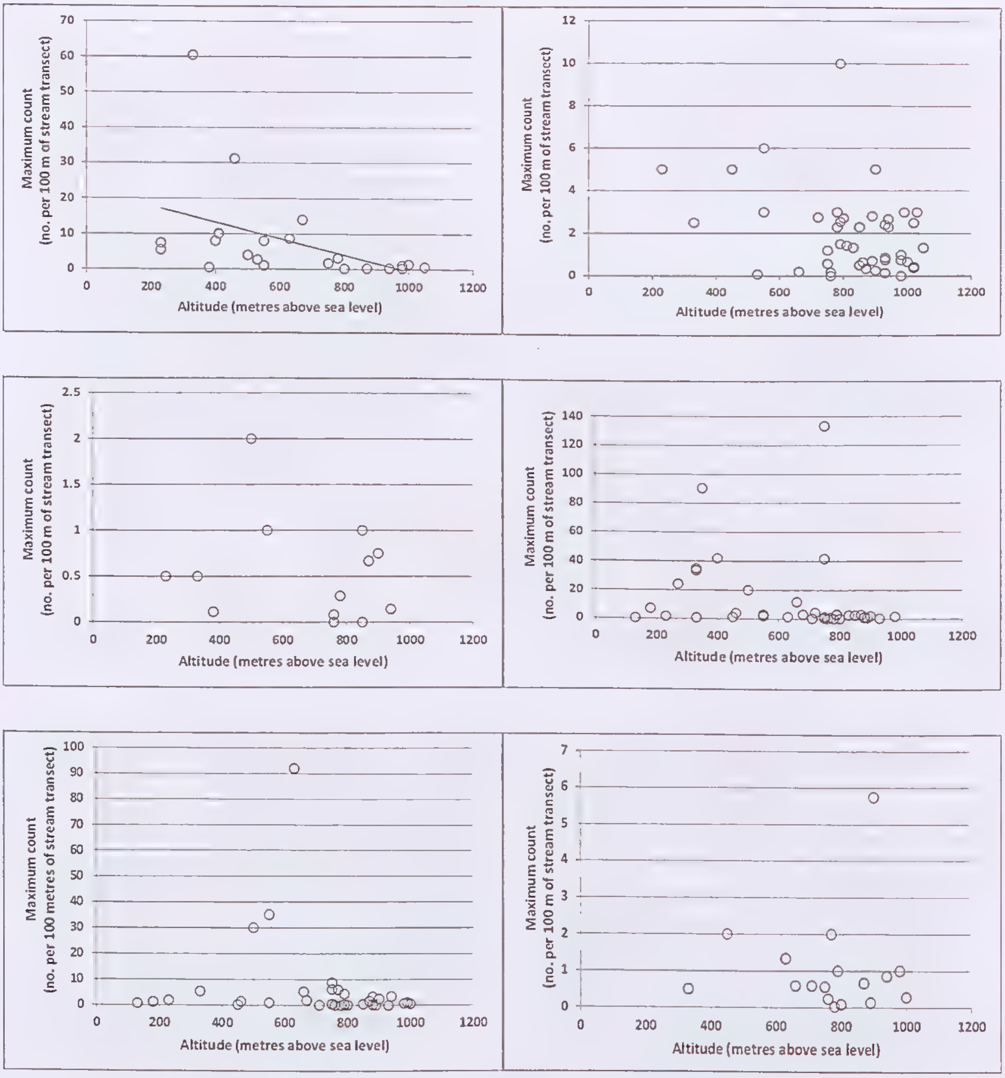


FIGURE 5. Altitudinal variation in counts of post-metamorphic animals at presence sites during QPWS surveys. The data points in these plots represent the maximum counts for each site standardised to 100 m of stream transect. Trendlines are included only for linear regression analyses with a p value less than 0.05.



During QPWS surveys, the abundance of *T. liemi* at presence sites was generally low, with numbers of post-metamorphic individuals rarely exceeding four animals per 100 m of stream transect (Figure 5). The relationship between altitude and abundance of *T. liemi* during these surveys (Figure 5) was unclear. On average, however, counts of *T. liemi* at sites above 800 m elevation were lower than counts at sites below 800 m altitude. Qualitative abundance data from the Hoskin surveys were consistent with the trends in the QPWS dataset.

Summary statistics for *T. liemi* counts from QPWS monitoring transects over the period 2000–2006 are provided in Table 5. Numbers of *T. liemi* at these transects varied considerably between censuses and there was no clear or consistent trend in count data during this period, with regression analyses returning non-significant results.

The majority of *T. liemi* records from our surveys were of animals calling from rock piles and crevices along smaller (first and second order) streams, or seepage areas and drainage lines adjoining larger streams. Numbers of *T. liemi* did not vary consistently between nocturnal or diurnal surveys (Table 5). During QPWS surveys, tadpoles of *T. liemi* were commonly sighted in shallow, silt-laden pools along smaller, gently flowing streams (Figure 7D). On occasion, *T. liemi* tadpoles were sighted on larger streams, though only in very low numbers and only during periods of low or basal flow. Spawn of *T. liemi* was not recorded during surveys; however, on one occasion early-stage tadpoles (Gosner stage 24–25) were located in seepage water in a narrow rock crevice. Although no sick or moribund *T. liemi* were observed during surveys, a number of animals collected for captive breeding in the late 2000s did test positive for amphibian chytrid fungus (Taudactylus Research and Husbandry Team, 2012).

Tusked Frog (Adelotus brevis)

During surveys, we recorded *A. brevis* at nineteen sites across five catchments, including Broken River, Cattle (North Branch), Finch Hatton, Massey and Rawsons Creek catchments (Figure 4C). Sites with *A. brevis* were situated between 230 m and 940 m altitude, with the majority of presence sites located between 350 m and 850 m altitude. Counts of *A. brevis* along QPWS stream transects were generally very low, with a maximum abundance of two animals per 100 m, and there was no clear relationship between altitude and the abundance at presence sites during surveys (Figure 5).

Whilst conducting surveys, *A. brevis* was recorded calling from isolated streamside pools in bedrock and seepage-fed pools adjoining streams, or occasionally the backwaters of large, slow-moving pools. Spawn and tadpoles of *A. brevis* were rarely seen, and no sick or moribund animals were observed.

Southern Orange-eyed Treefrog (Litoria chloris)

During surveys, *L. chloris* was recorded from 45 sites and 13 of the 16 creek catchments surveyed through 2000–2015 (Figure 4D). Sites at which *L. chloris* was recorded during surveys ranged in altitude from 130 m to 1020 m, with the majority of records above 500 m altitude. *Litoria chloris* was present at over 45% of sites above 350 m elevation, compared with 21% of sites below this altitude (Table 3).

During QPWS surveys, the abundance of *L. chloris* at presence sites ranged from one to 92 animals per 100 m of stream transect; however, numbers at most sites were low (<8 animals per 100 m). The very high counts of *L. chloris* recorded at some sites represent aggregations of calling males during irruptive breeding events. Sites with higher numbers were situated between 500 and 700 m elevation. Overall, however, there was no clear relationship between abundance and altitude in this species (Figure 5).

FIGURE 6. Count data for *T. eungellensis* from the QPWS monitoring transect at Dooloomai Falls (Left-hand Side) from 2000 through to 2006. This transect is situated at 550 m altitude in Finch Hatton Creek catchment (shown as 'D' in Figure 2B).

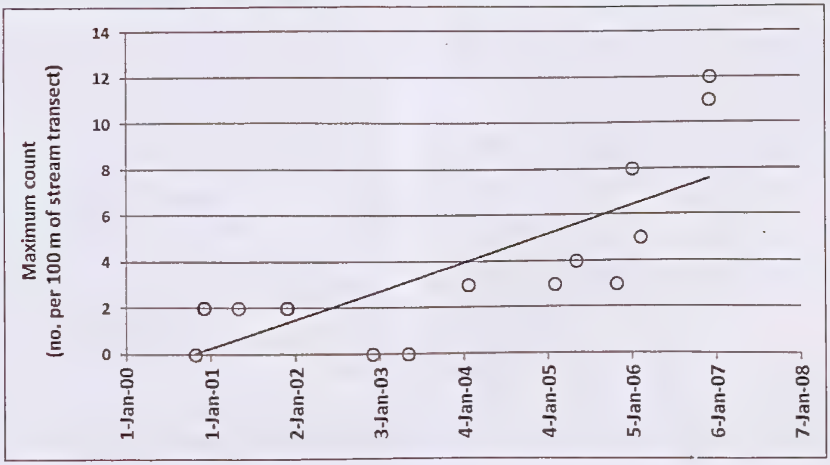


TABLE 5. Summary statistics and the results of linear regression analyses for count data from surveys undertaken at QPWS *T. liemi* monitoring transects from 2000 through to 2006. Regression analyses returning a non-significant result ($p > 0.05$) are denoted by the letters 'N.S.'. These data are based on counts of post-metamorphic animals from standardised censuses.

Site	**Maximum count**	**Median count**	**Mean diurnal count (mean ± s.e.m.)**	**Mean nocturnal count (mean ± s.e.m.)**	**Results of regression analysis**	**Number of standardised surveys (diurnal/ nocturnal)**
Dooloomai Falls (LHS)	8	1	2.38 ± 0.53	1.63 ± 0.34	N.S.	37 (21/16)
Dooloomai Falls (RHS)	6	1	1.77 ± 0.43	0.56 ± 0.29	N.S.	21 (12/9)
Tree Fern Creek	12	1	0.63 ± 0.26	2.71 ± 1.60	N.S.	15 (8/7)
Mt William Creek	15	2	3.44 ± 1.09	4.60 ± 1.37	N.S.	20 (10/10)
Mt David Creek	4	2	3.00 ± 1.00	2.67 ± 0.88	N.S.	8 (5/3)
Sunrise Creek	3	0	0.75 ± 0.41	0.50 ± 0.50	N.S.	14 (8/6)

L. chloris was most commonly recorded along streams with exposed bedrock containing isolated pools. Spawn and tadpoles were often found in these pools, while adult frogs were seen sitting out on rocks and vegetation along streams. On occasion (during periods of low or basal flow), tadpoles of *L. chloris* were also recorded from larger mid-stream pools. Three sick or dead *L. chloris* were recorded below 400 m altitude on Cattle (North Branch) and Rawsons Creeks during QPWS surveys. Sick *L. chloris* encountered at this time exhibited lethargy, but no other symptoms typical of amphibian chytridiomycosis.

Northern/Eastern Stony Creek Frog (Litoria jungguy/wilcoxii)

L. jungguy and/or *L. wilcoxii* were recorded at 60 sites between 130 m and 980 m altitude across fourteen of the sixteen creek catchments surveyed through 2000–2015 (Figure 8A). The abundance of post-metamorphic animals at presence sites ranged from one to 135 animals per 100 m of stream transect, with abundance levels at most sites low (<8 animals per 100 m of stream transect) (Figure 5). There was no obvious relationship between altitude and the abundance of *L. jungguy* and/or *L. wilcoxii* recorded at presence sites during surveys. On average, however, numbers at sites above 800 m altitude were lower than counts below 800 m (Figure 5). Due to problems separating *L. jungguy* and *L. wilcoxii* in the field, it is unclear how the current distribution and abundance of these species at Eungella might differ.

During surveys, *L. jungguy* and/or *L. wilcoxii* were recorded mainly from larger (third, fourth and fifth order), more open streams with animals seen sitting out on rocks, boulders and vegetation beside streams. Aggregations of breeding males were occasionally recorded at mid-altitude sites on more open streams/creeks, and tadpoles of *L. jungguy* and/or *L. wilcoxii* were occasionally recorded in slower-flowing sections of streams. Eight sick, moribund or dead *L. jungguy* and/or *L. wilcoxii* were recorded during QPWS surveys. Included in this tally were an adult and subadult found dead on Boulder Creek (at 260 m altitude); four sick and dead animals on Rawsons Creek (at 330 m altitude); and two animals at sites EU073 and EU076 in the lower Cattle Creek catchment (between 270 and 340 m altitude). In most cases, dead/moribund *L. jungguy* and/or *L. wilcoxii* were found sitting out in the open on rocks and boulders near streams. A number of sick and moribund *L. jungguy/wilcoxii* recorded during surveys exhibited symptoms consistent with amphibian chytridiomycosis, including lethargy, pallor and turgid (swollen) thighs, and one of these was confirmed as having chytridiomycosis (Berger, 2001).

Whirring Treefrog (Litoria revelata)

During surveys, we recorded *L. revelata* in low abundance (<3 animals per 100 m of stream transect) at just four sites, all above 900 m elevation in the headwaters of Cattle Creek North Branch (Figure 8B). Adult animals were mostly observed sitting out on low vegetation beside streams, with spawn and tadpoles recorded mainly from isolated pools in bedrock adjoining streams. Higher densities of *L. revelata* were recorded around farm dams in areas above 900 m elevation at Dalrymple Heights, adjoining Eungella National Park and in close proximity to stream sites occupied by this species.

FIGURE 7. (A) *T. eungellensis* habitat at Dooloomai Falls. (B) Adult *T. eungellensis* in splash zone of cascade on Rawsons Creek. (C) *R. vitellinus* habitat on Mt William Creek in the upper reaches of Cattle Creek (North Branch). (D) *T. liemi* habitat on first order stream in the upper reaches of Cattle Creek (North Branch). Photos A, C, D by E. Meyer; photo B by H. Hines.

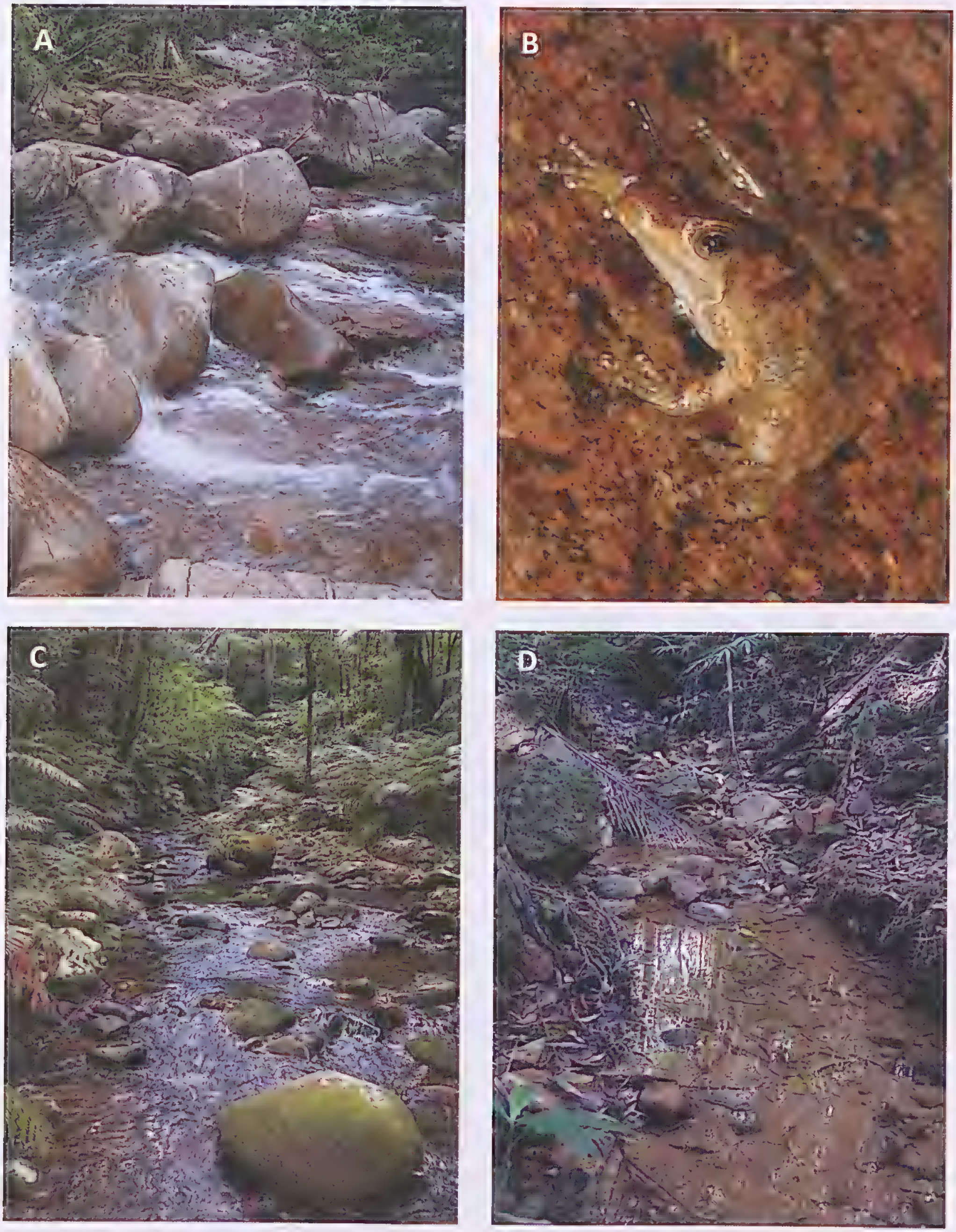
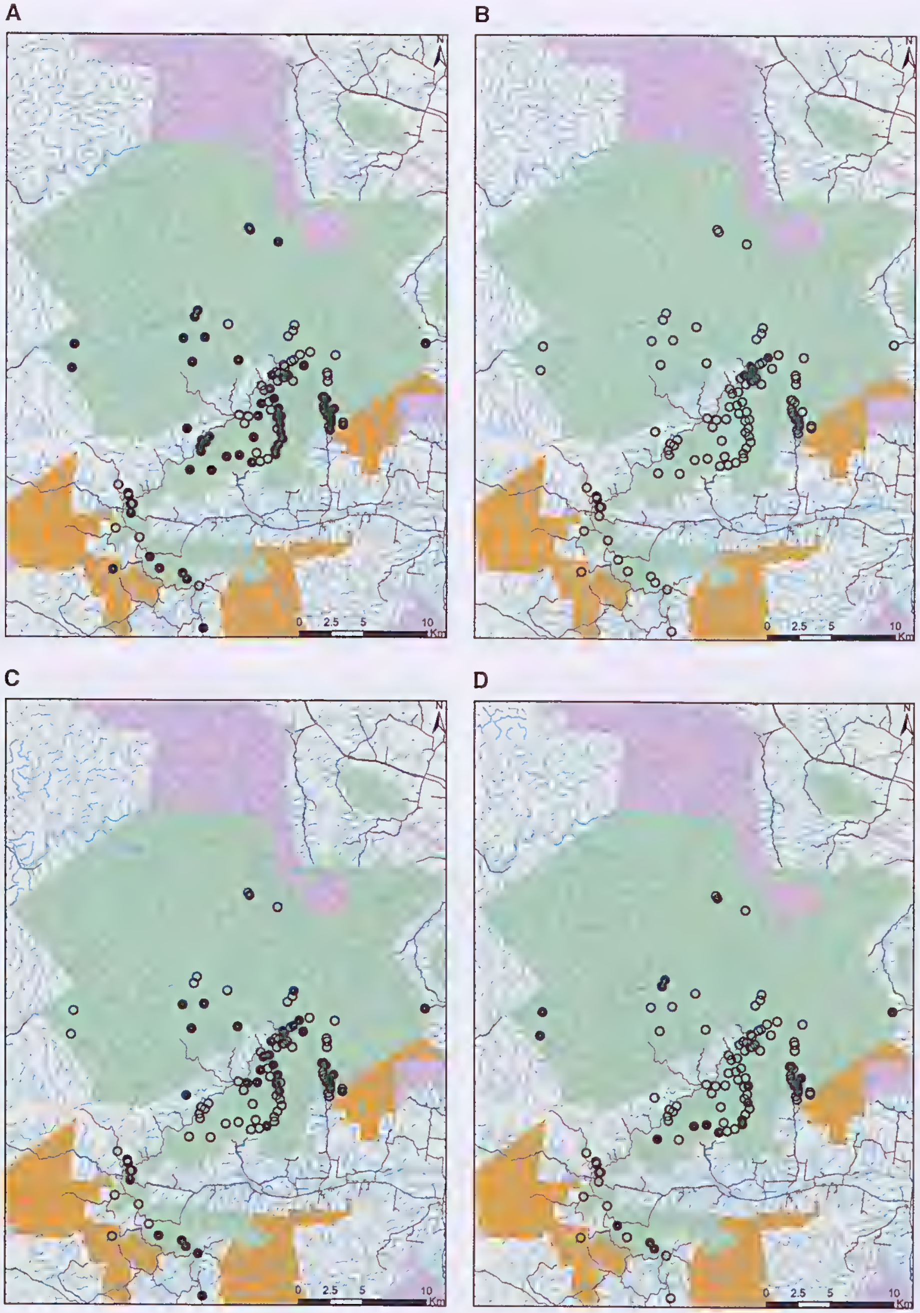


FIGURE 8. Distribution of frog species recorded during surveys from 2000 to 2015: (A) *L. wilcoxii/jungguy*; (B) *L. revelata*; (C) *M. fasciolatus*; and (D) *R. marina*. Presence sites represented by closed circles (●), absence sites represented by open circles (○). Refer to Figure 2 for a description of the features of the base map.



Great Barred Frog (Mixophyes fasciolatus)

M. fasciolatus was recorded at 34 sites across eight creek catchments, including Broken River, Amelia, Cattle (North and South Branches), Finch Hatton, Hazlewood, Massey and Rawsons Creeks (Figure 8C). During surveys, this species was recorded at sites between 300 m and 1000 m altitude. The proportion of sites with *M. fasciolatus* below 350 m was low (18%) compared with sites above 350 m altitude, where this species was present at 35–41% of sites surveyed (Table 3). The abundance of *M. fasciolatus* at presence sites was very low (<3 animals per 100 m of stream transect) irrespective of altitude (Figure 5).

Whilst conducting surveys, *M. fasciolatus* was primarily encountered on larger (third, fourth and fifth order streams) where adults were mostly heard and/or seen near water. Tadpoles of *M. fasciolatus* were observed mostly in deeper mid-stream pools and slow-flowing sections of stream. No sick, moribund or dead *M. fasciolatus* were recorded during surveys. However, small cysts containing trematode worms (*Fibricola* sp.) were noted on the tail and body of one tadpole that also tested positive for chytrid fungus (Berger, 2001; Murray *et al*., 2010). A separate series of five tadpoles collected in 2002 from Mt William Creek in the headwaters of Cattle Creek North Branch also tested positive for amphibian chytrid fungus (Symonds *et al*., 2007).

Other Frog Species

During surveys, a number of dry forest and/or pond-breeding frog species were occasionally recorded on stream transects, including the striped marshfrog (*Limnodynastes peronii*), scarlet-sided pobblebonk (*Limnodynastes terraereginae*), eastern sedgefrog (*Litoria fallax*), bumpy rocketfrog (*Litoria inermis*), broad-palmed rocketfrog (*Litoria latopalmata*), dusky gungan (*Uperoleia fusca*), and the introduced cane toad (*Rhinella marina*). The most commonly encountered of these species was *R. marina*, which was recorded at 39% of survey sites below 350 elevation, but only 11% or less of sites above 600 m altitude. Abundances of this and other dry forest species at presence sites were extremely low (<2 animals per 100 m of stream transect), and none of the aforementioned species were recorded breeding on stream transects during surveys. We recorded *R. marina* at 21 sites ranging in altitude from 130 to 790 m (Figure 8D). Densities of post-metamorphic *R. marina* at presence sites were very low (<2 animals per 100 m of stream transect) across all altitudes (Figure 5).

DISCUSSION

Status of R. vitellinus *and* T. eungellensis *at Eungella*

As with previous surveys in the 1980s and 1990s, we were unable to locate *R. vitellinus* on any of the stream sites surveyed through 2000–2015. With the last confirmed sighting of *R. vitellinus* over 30 years ago and repeated failure of surveys to locate this species, the likelihood of *R. vitellinus* surviving in the wild appears extremely low (but see 'Future Surveys', below).

In contrast with *R. vitellinus*, surveys were highly successful in locating *T. eungellensis*, with animals recorded at 32 sites within Eungella National Park. This represents a significant increase in the number of known presence sites compared with the mid-to-late 1990s. While potentially reflecting recovery of *T. eungellensis*, this increase is more likely the result of greater survey effort (increased number of survey sites and increased number and frequency of surveys) through 2000–2015.

During our surveys, *T. eungellensis* was recorded from many of the same creek catchments where Retallick (*pers. comm*., unpublished report) recorded this species in the 1990s, including Cattle Creek (North Branch), Finch Hatton Creek, Rawsons Creek and Tree Fern Creek. In addition to these catchments, *T. eungellensis* were also recorded from sites on Urannah Creek and Massey Creek, most of which are unlikely to have been surveyed for frogs previously. In contrast with surveys in the mid-to-late 1990s, we were unable to locate *T. eungellensis* at survey sites within the Boulder and St Helens Creek catchments. Additional surveys are therefore needed to assess the status of *T. eungellensis* in these catchments.

As with surveys in the mid-to-late 1990s, *T. eungellensis* was recorded across a broad altitudinal range (from 230 to 1050 m altitude), with the majority of presence sites situated below 600 m. Abundances of *T. eungellensis* during our surveys were also similar to those recorded in the 1990s and, with the exception of Rawsons Creek, well below abundance levels recorded prior to declines affecting this species and *R. vitellinus* in the mid-1980s (R. Retallick, *pers. comm*., unpublished report).

Numbers of *T. eungellensis* at monitoring transects through 2000–2006 were broadly similar to those recorded in the 1990s, with the notable exception of Dooloomai Falls (Left-hand Side) where numbers were much lower compared with those recorded by R. Retallick in the mid-1990s (R. Retallick, *pers. comm*., unpublished report). While the reasons for this decline are unclear, numbers of *T. eungellensis* at this site appeared to be increasing slowly through 2000–2006. Whether numbers at this site have subsequently recovered to mid-1990s levels (when Retallick recorded counts as high as 70 animals over 200 m of stream transect) is unknown. Count data at other monitoring transects did not show any obvious increase or decrease in numbers of *T. eungellensis* through 2000–2006. Whether the abundance of *T. eungellensis* at these sites has changed significantly since then is unclear, as regular monitoring and surveys at Eungella were discontinued after 2006.

While the persistence of *T. eungellensis* at sites within Eungella National Park is encouraging, numbers of *T. eungellensis* at most sites remain low compared with pre-decline levels, and recovery of this species appears to be occurring very slowly, at best. The continued absence of *T. eungellensis* at many historical sites, the consistently low abundance of animals at sites above 600 m, and apparent instability of populations at mid-to-high altitude sites, moreover, suggest the scope for future/ongoing recovery of *T. eungellensis* may be limited. Further surveys, monitoring and research are needed to determine whether this is actually the case or not, and if/how the recovery of *T. eungellensis* can be assisted (e.g. through translocations or by augmenting or re-establishing populations with captive-bred animals).

Status of Taudactylus liemi

During surveys through 2000–2015, *T. liemi* was recorded on numerous smaller streams at mid-to-high altitude (>600 m elevation) within Eungella National Park. The abundance of *T. liemi* at presence sites during this period was generally low, with numbers rarely exceeding 4 animals per 100 m of stream transect. How these numbers compare with abundance levels prior to 2000 is unclear, as abundance data for *T. liemi* from previous surveys are lacking.

Anstis (2013) stated that numbers of *T. liemi* at Eungella had declined since the late 1990s, but provided no data or references to support this claim. QPWS data from monitoring and surveys through 2000–2006 provide no clear evidence for such a decline, while subsequent observations/surveys by EM and CH through 2008–2015 are equivocal in this regard. Available evidence therefore does not appear to support Anstis' (2013) claim of a decline in numbers of *T. liemi* since the 1990s.

Status of Other Stream-dwelling Frogs at Eungella

During our surveys, *L. chloris* and *L. wilcoxii* and/or *L. jungguy* were commonly encountered at survey sites within Eungella National Park, as was the case during surveys and monitoring in the mid-to-late 1990s. In comparison, *M. fasciolatus* and *A. brevis* were encountered at relatively few sites during surveys, and only at very low densities (<2 animals per 100 m of stream transect). Although comparatively low, the number of sites supporting *A. brevis* during surveys through 2000–2015 greatly exceeds that during surveys in the mid-to-late 1980s, suggesting a possible recovery in *A. brevis* populations following an apparent decline in the mid-to-late 1980s (McDonald, 1990). It is possible, however, that the increased detectability of *A. brevis* at Eungella during surveys is the result of increased survey effort.

In contrast with other stream-dwelling hylids encountered during our surveys, *L. revelata* was recorded from only a handful of high-elevation streams in the headwaters of Cattle Creek North Branch and, incidentally, a small number of nearby farm dams at Dalrymple Heights. These few high-elevation sites are the only locations from which this enigmatic species is known in mid-eastern Queensland, with the next nearest populations of *L. revelata* occurring 500 km to the north, on the Atherton Tableland, and about 900 km south, along the Queensland/New South Wales border. Given the apparent paucity of sites supporting *L. revelata* in mid-eastern Queensland, more effort should be put into surveys and monitoring of this species at Eungella.

Due to difficulties differentiating between *L. wilcoxii* and *L. jungguy* in the field, the current status of these species at Eungella remains unclear. Widespread genotyping of stony creek frogs at Eungella is needed to better understand the distribution and abundance of these species at Eungella.

The Occurrence and Impact of Amphibian Chytrid Fungus at Eungella

The population declines documented at Eungella during the mid-1980s are almost certainly attributable to amphibian chytridiomycosis – an apparently exotic disease implicated in amphibian population declines elsewhere in eastern Australia and many other parts of the world (Retallick *et al.*, 2004; Murray *et al.*, 2010; Scheele *et al.*, 2017). During our surveys, we encountered a number of animals exhibiting symptoms consistent with this disease, including lethargy, pallor, and turgor of the thighs, a subset of which tested positive for Bd (the cutaneous fungal pathogen responsible for amphibian chytridiomycosis). Although the number of animals exhibiting signs/symptoms of chytridiomycosis was low, laboratory testing of sick and healthy frogs and tadpoles (e.g. Berger, 2001; Murray *et al.*, 2010; Symonds *et al.*, 2007) suggests this fungal pathogen is widespread at Eungella, with Bd detected in a range of frog species across a broad altitudinal range (from 330 to 980 m altitude).

The occurrence of Bd at Eungella was documented in a previous study by Retallick *et al.* (2004), who detected Bd in populations of *T. eungellensis* and *L. wilcoxii/jungguy* at sites between 230 and 550 m altitude during the mid-1990s, including the largest known population of *T. eungellensis* on Rawsons Creek (Retallick *et al.*, 2004). These authors concluded that populations of *T. eungellensis* at Eungella are now persisting with stable endemic infections of amphibian chytrid fungus. While monitoring data from lower-altitude sites support this view, data from higher-altitude streams are more equivocal in this regard, with *T. eungellensis* remaining scarce or absent at most high-altitude sites surveyed during the 1990s and 2000s. Monitoring data from Dooloomai Falls showing a sharp decline in numbers since the late 1990s are also equivocal in this regard, raising doubts about the stability of chytrid infections at mid-altitude sites. Further research on the prevalence of Bd infection amongst *T. eungellensis* populations across an altitudinal gradient is needed to better understand the influence of Bd on survival and recruitment of this species at mid- and high-altitude stream sites.

Although occurrence/abundance of *T. eungellensis* at higher-altitude sites may be heavily influenced by Bd, this does not appear to be the case for *T. liemi*, which, despite testing positive for Bd, was commonly encountered at mid- and high-altitude sites through 2000–2015, albeit at low densities. Whether the low abundances of *T. liemi* recorded during surveys are the result of Bd or other factors is unclear, as data on the abundance of this species before the mid-1980s are scarce. Given the involvement of Bd in declines of both the northern and Kroombit tinkerfrog (*T. rheophilus* and *T. pleione*), however, it seems unlikely that numbers of *T. liemi* would not have been impacted by Bd either now or in the past (Scheele *et al.*, 2017). Further research investigating the prevalence of Bd infection in *T. liemi* is needed to determine what, if any, impact Bd might have on the abundance of this species.

In contrast with *R. vitellinus* and *T. eungellensis*, there are insufficient data to assess the past and current impact of Bd on other stream-dwelling frogs at Eungella. Data on the prevalence and impact of Bd infection in these species are needed to better understand the influence of Bd on their distribution and abundance at Eungella.

Future Surveys

While surveys through the 1990s and 2000s have so far failed to locate *R. vitellinus*, many kilometres of stream habitat within Eungella National Park remain unsurveyed, so the persistence of this species should not be ruled out. As well as relict populations of *R. vitellinus*, unsurveyed streams within Eungella National Park could also support additional populations of *T. eungellensis* at similar densities to that observed on Rawsons Creek. Further surveys in remote and difficult-to-access parts of Eungella, focusing on streams at the lower altitudinal limit for both *T. eungellensis* and *R. vitellinus* (i.e. between 350 m and 550 m altitude), therefore should be encouraged. In particular, future surveys at Eungella should focus on westerly-aspect streams with low canopy cover (e.g. streams in the middle and upper reaches of Massey and Urannah Creeks) because these have acted as disease refuges for populations of stream frogs impacted by Bd in the Wet Tropics region (Puschendorf *et al.*, 2011). The impact of Bd on these streams may be limited because average conditions are warmer than is optimal for growth and reproduction of Bd (Puschendorf *et al.*, 2011). Additional areas to focus on include the St Helens Creek and Northern Urannah Creek catchments north to Mt MacCartney, where considerable areas of rainforest stream habitat have received very little survey attention, either historically (see Figure 1) or recently (see Figure 2).

The rediscovery and persistence of *T. eungellensis* on streams at Eungella offer hope for the continued existence of the sharp-snouted dayfrog (*Taudactylus acutirostris*) in the Wet Tropics of North Queensland. Like *T. eungellensis*, this once-common species suffered significant declines attributable to chytridiomycosis in the late 1980s and early 1990s and has not been sighted in the wild since 1997 (Marshall, 1997; Northern Queensland Threatened Frogs Recovery Team, 2001). Given the extent of unsurveyed stream habitat in the Wet Tropics, more effort should be put into locating relictual populations of this species. As with future surveys targeting *T. eungellensis*, surveys for *T. acutirostris* should target more open streams near the lower altitudinal limit reported for this species (i.e. around 350 m altitude, Hoskin & Hero, 2008).

ACKNOWLEDGEMENTS

The authors thank QPWS staff based at Eungella and Rockhampton and the many volunteers who assisted with surveys at Eungella through 2000–2006. In particular, we thank Denis Jeffery for assistance with monitoring, and Jodi Jardine, Brett Manning and Jesse Rowland for data management. CH would like to thank the National Environmental Research Program (NERP) and the Norden's Ark Foundation for funding, and Megan Higgie, Anders Zimny, George Madani, Claes Andren and Marcus Strinning for assistance in the field. We also thank members of the Mackay Bushwalkers' Club for contributing additional records of *T. eungellensis* from within the Cattle Creek catchment.

This work was undertaken under various animal care and ethics approvals granted to QPWS and James Cook University staff. Surveys by C. Hoskin were conducted under Scientific Purposes Permit Number WITK13825813.

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THE AVIFAUNA OF THE EUNGELLA REGION, CENTRAL COASTAL QUEENSLAND, AUSTRALIA

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The Eungella region of the Clarke Range, located in central coastal Queensland, Australia, represents a 'bridge' between the avifauna of the tropics and that of the subtropics. In this paper, we collate species records from automated acoustic recordings and field observations made during the Griffith University and Queensland Museum surveys of Eungella National Park and Pelion State Forest in 2013 and 2014, bird observations uploaded to the eBird database, and information available from local birders. So far, 236 bird species have been recorded in the Eungella region, representing 67 families – 36.4 per cent of the total of 648 species known from Queensland. Eungella National Park protects the core range of a species endemic to the Clarke Range, the Eungella Honeyeater (*Bolemoreus heinwoodi*), as well as numerous endemic subspecies and isolated populations of subtropical species. Many of these species and subspecies are restricted to cool upland rainforest and, as a consequence, are seriously threatened by climate change.

Keywords: Eungella, birds

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INTRODUCTION

Eungella National Park (ENP) and the adjoining forests of the Clarke Range represent the largest continuous areas of remnant rainforest on the central Queensland coast. ENP protects approximately 50,800 hectares of largely upland rainforest and was established in 1941 (Moon & Moon, 2002). The immediate surrounds comprise a mixture of wet and dry sclerophyll forest, as well as farmland, settlements and open country. Moving further afield, the landscapes to the north and south of ENP are characterised by lowland zones of warm, open and dry habitats that are unsuitable for rainforest species (Bryant & Krosch, 2016). The landscape to the west becomes increasingly arid with distance from the Great Dividing Range. The Clarke Range and ENP, then, can be seen as relatively cool, moist mountain refugia of the formerly widespread Miocene rainforests that dominated the Australian landscape 5.3 million years ago (Weber *et al*., 2014; Bryant & Krosch, 2016).

The inhospitable lowland habitats to the north and south of Eungella are known as the Burdekin Gap and the St Lawrence Gap, respectively, and represent biogeographic barriers to the dispersal of rainforest species. As a consequence, ENP is effectively isolated from other extensive tracts of rainforest: the southernmost areas of the Wet Tropics bioregion are some 300 kilometres to the north, and the Conondale Ranges are approximately 650 km to the south. We note, however, that the St Lawrence Gap is only approximately 100 km wide (Bryant & Krosch, 2016) and that there are smaller remnant rainforest patches within that 650 km expanse (e.g. Kroombit Tops), that may have provided 'stepping stones' for the historical dispersal and/or contraction of rainforest species. Due to this biogeographic history, the avifauna of the Eungella region is made up of a unique mix of subtropical and tropical species.

Despite the obvious biological significance of the Eungella region, there had been few systematic biodiversity surveys conducted in the area (with some notable exceptions – see Anderson (2011) and Crouther & Crouther (1999) for examples) until the Eungella Biodiversity Survey (EBS) of 2013–14 – a joint project of Griffith University and the Queensland Museum. The aim of this project was to quantify the biodiversity of birds, plants and selected invertebrate groups along an elevational gradient from 200 m to 1200 m asl within ENP and the adjacent Pelion State Forest (Ashton *et al*., this volume). Here we describe the avifauna of the Eungella region, based on the results of surveys made during the EBS by EL in 2013 and 2014, incidental observations made by EL and CJB during the same time period, records from the eBird database, and records from local observers. We discuss the elevational distribution of the avifauna within ENP, include notes on the distributions of the species and subspecies occurring in the broader Eungella region, and conclude with a general discussion of the region's avifauna.

METHODS

Records from ENP and Pelion State Forest (SF) made during the EBS are included here, along with records from Eungella village, Crediton SF, the upper Pioneer Valley and the area around Eungella Dam. These areas are included in an attempt to represent accurately the avifauna of the broader Eungella region. The methodology employed by EL during the EBS is described in detail in Leach *et al*. (2015). Briefly, field work was conducted in two sessions between 4 November and 1 December 2013, and between 19 March and 15 April 2014. Automated acoustic recordings were made of the soundscape at each of 24 sites in ENP and Pelion SF. Sites were situated in six elevational bands; each elevational band was separated by 200 m. Therefore, there were four replicate sites at 200 m, 400 m, 600 m, 800 m, 1000 m and 1200 m above sea level (asl). EL also conducted multiple-point visual and aural counts at each site throughout each survey period. Incidental observations were recorded by EL and CJB during travel to and from sites during the survey periods. EL interrogated the eBird database and included records of species from hotspots within the areas described above, and those from Marion Crouther's 2010 bird list for Eungella (see www.eungella.info/birds.htm and Crouther & Crouther, 1990).

RESULTS AND DISCUSSION

Based on our surveys, published literature and observational records obtained from eBird, a total of 236 bird species representing 67 families have been reliably recorded in the broader Eungella region (Table 1). A synopsis of each family given in taxonomic order is presented below; the taxonomy adopted is the IOC Checklist v 9.1 (Gill & Donsker, 2019). The synopsis is followed by Table 1, which provides detailed notes on the species found in the region. Where possible, information is given at the subspecific level; this information is taken from Menkhorst *et al*. (2017) and supplemented by Simpson & Day (2004). In certain cases, the relevant edition of the *Handbook of Australian, New Zealand and Antarctic Birds* was also consulted.

Casuariiformes

Casuariidae

Australia's largest bird, the Emu (*Dromaius novaehollandiae*), is the sole surviving member of its genus. Found throughout most of Australia, Emus are mainly restricted to the dry country west of the Clarke Range in the Eungella region.

Anseriformes

Anseranatidae

The Anseranatidae or magpie-geese are an ancient lineage of waterfowl, which diverged before all other ducks, geese and swans (Sraml *et al*., 1996). There is only one extant species in the family, the Magpie Goose, *Anseranas semipalmata*. Magpie Geese are common in freshwater wetlands throughout tropical and subtropical regions of Australia.

Anatidae

The Eungella region is home to nine anatids, most of which are widely distributed in Australia. Some species, such as the pygmy geese (*Nettapus* spp.) and the Rajah Shelduck (*Tadorna raja rufitergum*) are not commonly found in the subtropics to the south.

Galliformes

Megapodiidae

The megapodes are an ancient avian clade, and are represented in the Eungella region by two species – the Australian Brushturkey (*Alectura lathami lathami*) which is distributed along most of the east coast, and the Orange-footed Scrubfowl (*Megapodius reinwardt tumulus*), occurring here at the southern limit of its range. The elevational distributions of the two species potentially reflect their broader distributions, with the widespread Brushturkey occurring at all elevations and the Scrubfowl restricted to the warm, moist forest in the lowlands. Males of both species build large nest mounds of leaf litter and other organic matter that they collect from the forest floor (Jones & Goth, 2008).

Phasianidae

Brown Quail (*Coturnix ypsilophora*) and King Quail (*Excalfactoria chinensis victoriae*) are known to occur sporadically in Eungella township as part of irruptive events in the summer wet season, along with several species of buttonquail (Turnicidae – see below) (Crouther & Crouther, 1999). Stubble Quail (*C. pectoralis*) also has potential to irrupt, but is yet to be reliably recorded in the region.

Podicipediformes

Podicipedidae

The grebes are freshwater diving birds. Three species are known to occur in the Eungella region: Australasian Grebe (*Tachybaptus novaehollandiae*), Great Crested Grebe (*Podiceps cristatus australis*) and Hoary-headed Grebe (*Poliocephalus poliocephalus*). The former may be found on a range of freshwater wetlands including small farm dams, while the latter two species probably only occur regularly at Eungella Dam.

Pelicaniformes

Threskiornithidae

The ibises and spoonbills are well represented in Australia, with five species typically inhabiting freshwater wetlands. All five species – Australian White Ibis (*Threskiornis molucca*), Straw-necked Ibis (*T. spinicollis*), Glossy Ibis (*Plegadis falcinellus*), Royal Spoonbill (*Platalaea regia*) and Yellow-billed Spoonbill (*P. flavipes*) – can be found around Eungella.

Ardeidae

The herons and egrets found in the Eungella region are widespread species that occur over much of the eastern half of Australia. They include the Nankeen Night-heron (*Nycticorax caledonicus*), the Eastern Cattle Egret (*Bubulcus coromandus*), White-necked and White-faced Herons (*Ardea pacifica* and *Egretta novaehollandiae*, respectively) and Great, Intermediate and Little Egrets (*A. alba*, *A. intermedia* and *E. garzetta*, respectively).

Pelicanidae

In Eungella, as well as Australia more broadly, there is only one member of this widespread family – the Australian Pelican (*Pelecanus conspicillatus*).

Suliformes

Phalacrocoracidae

Five species of cormorant are found in mainland Australia. Four of these – Great (*Phalacrocorax carbo*), Australian Pied (*P. varius*), Little Pied (*Microcarbo melanoleucos*) and Little Black (*P. sulcirostris*) Cormorants – can be found in the Eungella region.

Anhingidae

The Australasian Darter (*Anhinga novaehollandiae*) is the only member of this family found in Australia.

Accipitriformes

Pandionidae

The Eastern Osprey (*Pandion haliaetus*) is the only member of this family found in the Eungella region.

Accipitridae

Many of Australia's diurnal birds of prey belong to this family, the largest within the Accipitriformes, and thirteen species (five kites, a baza, an eagle, two goshawks, a sparrowhawk, two harriers and a sea eagle) can be found in the Eungella region. The high diversity of raptors, with varied habitat requirements and foraging strategies, reflects the wide variety of habitats found around Eungella. For subspecific information, see Table 1.

Otidiformes

Otididae

The Australian Bustard (*Ardeotis australis*) is the only member of this family found in Australia, and records in the Eungella region are restricted to open woodland or grasslands in the western extremities of the area.

Gruiformes

Rallidae

The rails have an almost cosmopolitan distribution. There are seven representatives of this family (a rail, a bush-hen, a crake, a swamphen, a moorhen, a native hen and a coot) occurring in the Eungella region – all with fairly widespread distributions in Australia. The diversity in the Rallidae reflects the diversity of habitats available in the region – a pattern that is repeated for many other families. For subspecific information, see Table 1.

Gruidae

The Brolga (*Grus rubicunda*) is the only representative of the crane family in the Eungella region.

Charadriiformes

Turnicidae

There are seven Australian buttonquail species, and some are prone to irruptive events. Crouther & Crouther

(1999) described semi-annual irruptions of buttonquail and true quail in Eungella township in the summer wet season. During irruption events, they are presumably attracted to lights of the township while travelling after dark. Red-backed (*Turnix maculosa*), Red-chested (*T. pyrhhothorax*), Painted (*T. varia varius*) and Little (*T. velox*) Buttonquails have all been recorded in the region.

Burhinidae

Bush Stone-curlew (*Burhinus grallarius*) is the only member of its family to occur in the Eungella area.

Recurvirostridae

The White-headed Stilt (*Himantopus leucocephalus*) is the only member of this family occuring around Eungella. Surprisingly, there are no records from Eungella Dam.

Charadriidae

Plovers and dotterels are well represented in Australia, with 20 species, four of which occur in the Eungella region: Banded (*Vanellus tricolor*) and Masked Lapwings (*V. miles*), and Red-kneed (*Erythrogonys cinctus*) and Black-fronted Dotterels (*Elseyornis melanops*). Eungella is in the Masked Lapwing hybrid zone: intermediate forms between the subspecies *V. miles miles* and *V. m. novaehollandiae* may occur in the region.

Scolopacidae

The snipes and sandpipers are a large family, with many migratory species. Including vagrants, 45 scolopacids have been recorded in Australia. The only regularly occurring member of this family in the Eungella region is Latham's Snipe (*Gallinago hardwickii*). Sharp-tailed Sandpipers (*Calidris acuminata*), along with other calidrines, may occur but have yet to be officially recorded. This is probably more a function of the lack of survey effort in the region as opposed to true absence.

Laridae

Four representatives of this widespread family occur in the Eungella region: Silver Gull (*Chroicocephalus novaehollandiae*), Gull-billed Tern (*Gelochelidon nilotica*), Caspian Tern (*Hydroprogne caspia*) and Whiskered Tern (*Chlidonias hybrida*).

Columbiformes

Columbidae

Pigeons are diverse in the Eungella region and are represented by 17 species in 11 genera. These include seven species associated with rainforests: Wompoo Fruit-dove (*Ptilinopus magnificus keri*), Rose-crowned Fruit-dove (*P. regina regina*), Superb Fruit-dove (*P. superbus*), Pacific Emerald Dove (*Chalcophaps longirostris chrysochlora*), White-headed Pigeon (*Columba leucomela*), Brown Cuckoo-dove (*Macropygia phasianella robinsoni*), and Topknot Pigeon (*Lopholaimus antarcticus*). Seven other species are more commonly found in drier, open habitats such as woodlands and exotic gardens: Crested Pigeon (*Ocyphaps lophotes lophotes*), Peaceful Dove (*Geopelia placida placida*), Bar-shouldered Dove (*G. humeralis humeralis*), Diamond Dove (*G. cuneata*), Squatter Pigeon (*Geophaps scripta scripta*), Wonga Pigeon (*Leucosarcia melanoleuca*) and Common Bronzewing (*Phaps chalcoptera*). Two introduced species, Spotted Dove (*Streptopelia chinensis*) and Rock Dove (*Columba livia*), are also commonly recorded in the region, along with the migratory Torresian Imperial Pigeon (*Ducula spilorrhoa*).

Cuculiformes

Cuculidae

The cuckoos are largely nest parasites. Eleven species occur in the Eungella region. Some, such as the Pacific Koel (*Eudynamys orientalis subcyanocephala*), Channel-billed Cuckoo (*Scythrops novaehollandiae*) and Oriental Cuckoo (*Cuculus optatus*) are migratory and are only present in the summer months. Others are year-round residents. Some species, such as Shining Bronze-cuckoo (*Chrysococcyx lucidus*), Little Bronze-cuckoo (*C. minutillus minutillus*), Fan-tailed Cuckoo (*Cacomantis flabelliformis*) and Brush Cuckoo (*Cacomantis variolosus variolosus*) prefer rainforest and associated wet sclerophyll forest. Others, like Black-eared Cuckoo (*Chrysococcyx osculans*), Pallid Cuckoo (*Cacomantis pallidus*), Horsefield's Bronze-cuckoo (*Chrysococcyx basalis*) and 'Gould's Bronze-cuckoo' (*Chrysococcyx minutillus russatus*) prefer the more open habitat to the west of Eungella. The final cuckoo species found in the region, the Pheasant Coucal (*Centropus phasianinus phasianinus*), is not a nest parasite and can be found anywhere in association with tall, dense grasses.

Strigiformes

Tytonidae

The 'Tytos', or barn owls, recorded in Eungella include the Greater Sooty Owl (*Tyto tenebricosa*), mostly restricted to eastern Australia and southern Papua New Guinea, and the widely distributed Eastern Barn Owl (*T. delicatula*). The occurrence of Greater Sooty Owl in the region is of interest as the population is isolated from those to the south (Conondale Range, south-eastern Queensland) and north (Papua New Guinea). There is potential for two other *Tyto* species to occur in the region: Australian Masked Owl (*T. novaehollandiae*) and the Eastern Grass Owl (*T. longimembris*).

Strigidae

Another owl genus, *Ninox*, is well represented in Eungella, with four species recorded: Rufous Owl (*N. rufa queenslandica*), Powerful Owl (*N. strenua*), Southern Boobook (*N. boobook boobook*) and Barking Owl (*N. connivens connivens*).

Caprimulgiformes

Podargidae

The podargids are represented in Eungella by a single species: Australia's most common frogmouth, the Tawny Frogmouth (*Podargus strigoides strigoides*).

Caprimulgidae

Three species of nightjar can be found in the Eungella region: White-throated Nightjar (*Eurostopodus mystacalis*) and Large-tailed Nightjar (*Caprimulgus macrurus*) in relatively moist habitats, and Spotted Nightjar (*Eurostopodus argus*) in drier western areas of the region. The spectacular calls of each species are often the best way to detect their presence; they are very well camouflaged, with cryptic plumage patterns.

Apodiformes

Aegothelidae

The Australian Owlet-nightjar (*Aegotheles cristatus*) is the only species from this family to be found in Australia. Owlet-nightjars are often detected by call, or seen resting on tracks or roads at night.

Apodidae

The swifts and swiftlets are aerial insectivores that spend much of their life on the wing. Two species found in Eungella are migratory: the White-throated Needletail (*Hirundapus caudacutus*) and Pacific Swift (*Apus pacificus*) are present only in the austral summer. The other apodid found in the region is a breeding resident. Small colonies of the Australian Swiftlet (*Aerodramus terraereginae terraereginae*) inhabit and breed in two caves in Finch Hatton Gorge (D. Barnes, *pers. comm.*).

Coraciiformes

Coraciidae

The Oriental Dollarbird (*Eurystomus orientalis*) is a migratory species present in the Eungella region in summer. Dollarbirds are often seen perched on telephone lines, or the exposed branches of dead trees.

Alcedinidae

The kingfishers are represented by seven species in the Eungella region. The migratory Buff-breasted Paradise Kingfisher (*Tanysiptera silva*) breeds only in terrestrial termite mounds in the lowland rainforests and is present during summer. Laughing and Blue-winged Kookaburras (*Dacelo novaeguineae* and *D. leachii*) usually select arboreal termite mounds or tree hollows for breeding, and can be found in the rainforest and open country in the Eungella region. Azure Kingfishers (*Ceyx azureus azurea*) are sometimes seen along rainforest streams. Moving away from the rainforest, into the drier country around Eungella Dam or down the Pioneer Valley, may lead to sightings of three *Todiramphus* species: Forest Kingfisher (*Todiramphus macleayii incinctus*), Sacred Kingfisher (*T. sanctus sanctus*) and, more rarely, Red-backed Kingfisher (*T. pyrhhopygius*).

Meropidae

The Rainbow Bee-eater (*Merops ornatus*), a bird of watercourses and open country, is the only bee-eater present in Australia. Bee-eaters construct nest tunnels in earthen banks, and are acrobatic in their aerial pursuit of insect prey.

Falconiformes

Falconidae

The regularly occurring falcons of the Eungella region include the Nankeen Kestrel (*Falco cenchroides*), Australian Hobby (*F. longipennis*), Brown Falcon (*F. berigora*) and Peregrine Falcon (*F. peregrinus*). Black Falcon (*F. subniger*) has the potential to occur in the region, but there are no records to date.

Psittaciformes

Cacatuidae

Six species of cockatoo have been recorded in the Eungella region. Three are widespread in Australia: the Galah (*Eolophus roseicapilla kuhli/albiceps*), Little Corella (*Cacatua sanguinea gymnopsis*), and Sulphur-crested Cockatoo (*Cacatua galerita galerita*). Three species of black-cockatoo – the frequently occurring Red-tailed Black-cockatoo (*Calyptorhynchus banksii banksii*), and the infrequent Glossy and Yellow-tailed Black-cockatoos (*C. lathami erebus* and *C. funereus funereus*, respectively) – are also found in the region.

Psittaculidae

Parrots occurring in the Eungella region include seven species: the Australian King Parrot (*Alisterus scapularis*) and Red-winged Parrot (*Aprosmictus erythropterus*), Crimson and Pale-headed Rosellas (*Platycercus elegans* and *P. adscitus*), and the primarily nectivorous lorikeets represented by Rainbow (*Trichoglossus moluccanus moluccanus*), Scaly-breasted (*T. chlorolepidotus*) and Little (*Parvipsitta pusilla*) Lorikeets. Crimson Rosellas are restricted to high-elevation rainforest in the region. The subspecies occurring in Eungella was described as a distinct subspecies, *Platycercus elegans filewoodi*, by McAllan & Bruce (1989). Schodde & Mason (1997), however, subsequently synonymised *P. e. filewoodi* with *P. e. elegans*. The uncertain status of the subspecies continues to this day: Menkhorst *et al*. (2017) treat it as an isolated population of the Wet Tropics subspecies *P. e. nigrescens*. Photographs of Crimson Rosellas from Eungella, as well as the two specimens from the Eungella region in the Queensland Museum examined by EL and CB, show extensive black mottling on the mantle, and a slightly darker red tone to the plumage compared with the southern, nominate subspecies *P. e. elegans* – both features shared with *P. e. nigrescens*. However, dedicated genetic work on the Eungella population will be required in order to determine its status.

Passeriformes

The passerines are the largest order of birds, including more than half of all extant species. They are distinguished by the arrangement of their toes, with three forward-facing toes and one backwards-facing toe facilitating perching – this is why the passerines are sometimes referred to as 'perching birds'.

Pittidae

The pittas are represented in the Eungella region by a single species: the Noisy Pitta (*Pitta versicolor intermedia*). Noisy Pittas are very common in the rainforests around Eungella, perhaps due to a lack of competition from Logrunners or Chowchillas.

Ptilonorhynchidae

The bowerbirds are an ancient lineage of passerines, famous for the male's construction of a bower, an elaborate structure to attract females during the breeding season. In the dry country to the west of Eungella, Great Bowerbirds (*Chlamydera nuchalis orientalis*) may be found. In the rainforest, above 1000 m elevation, an isolated population of Regent Bowerbirds (*Sericulus chrysocephalus*) exists. These birds are at the extreme northern limit of their distribution, and as such, Regent Bowerbirds in the Eungella region are under significant threat from climate change. Continued climatic warming may lead to the local extinction of this species (Anderson, 2011).

Climacteridae

The treecreepers are represented by a single species in Eungella: the White-throated Treecreeper (*Cormobates leucophaea intermedia*). The subspecies which occurs in Eungella is restricted to the Clarke and Connors Ranges, and occurs between the northerly subspecies *minor* (Wet Tropics) and the *metastasis* subspecies of south-eastern Queensland and north-eastern New South Wales (Boles & Longmore, 1983).

Maluridae

The Australian wrens include the fairywrens, emuwrens and grasswrens. In Eungella, the only malurid that occurs is the Red-backed Fairywren (*Malurus melanocephalus melanocephalus*).

Meliphagidae

Australia is home to roughly half (77) of the species in this family. In the Eungella region, 19 species of honeyeater, representing 14 genera, occur. The Eungella Honeyeater (*Bolemoreus hindwoodi*) was described in 1983 and is endemic to the region (Longmore & Boles, 1983). In general, the species is restricted to higher-elevation rainforest (above approximately 800 m asl) and is threatened by climate change. There is some evidence that the Eungella Honeyeater undertakes seasonal elevational migration (D. Barnes, *pers. comm*.), moving into lower elevations of ENP and Crediton State Forest in winter, though more data is required to understand its seasonal movements. For subspecific information on the rest of Eungella's honeyeaters, see Table 1.

Pardalotidae

Two of Australia's four pardalote species occur in Eungella: Spotted (*Pardalotus punctatus punctatus*) and Striated (*P. striatus melanocephalus*) Pardalotes. Interestingly, *P. punctatus militaris* (the subspecies from the Wet Tropics) may occur in sympatry with the nominate subspecies in the Eungella region.

Acanthizidae

The 'Australasian warblers' are represented in the Eungella region by two scrubwrens (*Sericornis* spp.), four *Gerygone* species, the Weebill (*Smicrornis brevirostris brevirostris*) and three thornbills (*Acanthiza* spp.). The subspecific status of some acanthizid species in the region is poorly known, and there are several isolated subspecies. The White-browed Scrubwren (*S. frontalis laevigaster*) that occurs in Eungella is in the middle of the distribution of this subspecies on the Queensland coast. Large-billed Scrubwrens in the region are likely to be the nominate subspecies *magnirostra*, here at the northern limit of its range. We note, however, that the population here is also isolated by biogeographic barriers. Conversely, Large-billed Gerygone (*G. magnirostris cairnsensis*) appears to be near the southern limit of its range in the region. White-throated and Fairy Gerygones (*G. olivacea olivacea* and *G. palpebrosa flavida*) are fairly common in suitable habitat along the Queensland coast. The Brown Gerygone (*G. mouki amalia*) occurring in Eungella is another isolated subspecies. Brown Thornbill (*A. pusilla*) has a similar distribution to Large-billed Scrubwren; the population at Eungella is an isolated northern outlier of the southern subspecies *A. p. dawsonensis*. Weebills occur to the west of Eungella Dam, and Buff-rumped Thornbills (*A. reguloides squamata*) occur in drier sclerophyll forests to the south of ENP, such as Crediton SF. Records of Striated Thornbill occurring in Eungella on eBird are almost certainly misidentified Brown Thornbills or Yellow Thornbills (*Acanthiza nana modesta*) which occur here at the northern limit of the subspecies' range.

Psophodidae

The Eastern Whipbird, *Psophodes olivaceous olivaceous*, is the sole member of this family occurring in the Eungella region and is an isolated population. Their distinctive whip-like call is probably the easiest way to detect their presence.

Artamidae

The family Artamidae contains the woodswallows, the butcherbirds and their phylogenetic allies. Woodswallows can be highly irruptive: of Australia's six species, only one (Little Woodswallow *Artamus minor*) has yet to be recorded in the region. Black (*Cracticus quoyi rufescens*), Grey (*C. torquatus torquatus*) and Pied (*C. nigrogularis nigrogularis*) Butcherbirds can all be found in Eungella; Pied is by far the most common. The artamid list for the region is completed by the Australian Magpie (*C. tibicens*) and Pied Currawong (*Strepera graculina graculina*).

Campephagidae

The cuckooshrikes and allies are a family largely confined to the tropics and subtropics. In Eungella, there are six representatives: three cuckooshrikes (*Coracina* spp.), the Common Cicadabird (*C. tenuirostris tenuirostris*) and two trillers (*Lalage* spp.). See Table 1 for subspecific information.

Neosittidae

One species from this family, the Varied Sittella (*Daphoenositta chrysoptera*), occurs in Australia. In the Eungella region, the subspecies *D. chrysoptera leucocephala* is at the northern limit of its range; however, Eungella is a hybrid zone, where intergrades between *D. c. leucocephala* and *D. c. striata* could occur.

Pachycephalidae

This is a large Australasian family. In Eungella, four species representing two genera can be found. Both Golden (*Pacycephala pectoralis pectoralis*) and Rufous (*P. rufiventris rufiventris*) Whistlers are common in suitable habitat, as are Little (*Colluricincla megarhyncha synaptica*) and Grey (*C. harmonica harmonica*) Shrikethrushes.

Oriolidae

Two of Australia's three oriolid species can be found in the Eungella region: the Olive-backed Oriole (*Oriolus sagittatus sagitattus*) and the Australasian Figbird (*Sphecotheres vieilloti vieilloti*).

Dicruridae

The single representative of this family in Australia, the Spangled Drongo (*Dicrurus bracteatus bracteatus*), occurs at Eungella.

Rhipiduridae

The fantails are well represented in Eungella, with three of Australia's six species occurring in the region. These include the Willie Wagtail (*Rhipidura leucophrys leucophrys*), and Grey and Rufous Fantails (*R. albiscapa keasti*, and *R. rufifrons intermedia*, respectively).

Monarchidae

The Eungella region hosts six species of this family, representing five genera. Spectacled (*Symposiachrus trivirgatus melanorrhoa*), Black-faced (*Monarcha melanopsis*) and White-eared (*Carterornis leucotis*) Monarchs can all be found in the rainforests; the

Magpie-Lark (*Grallina cyanoleuca cyanoleuca*) is a bird of open country; and, Leaden and Restless Flycatchers (*Myiagra rubecula yorki* and *M. inquieta*) can be found in sclerophyll forests.

Corvidae

Two corvids can potentially be found in Eungella: the Torresian Crow (*Corvus orru*) and the Australian Raven (*Corvus coronoides coronoides*). However, recent records of *C. coronoides* in the eBird database examined by EL were misidentified *C. orru*: the status of the former in the region is therefore questionable (though we note that Marion Crouther (2010) includes it in her bird list for Eungella).

Corcoracidae

Both mud-nesters, the White-winged Chough (*Corcorax melanorhamphos melanorhamphos*) and the Apostlebird (*Struthidea cinereal dalyi*), occur in the dry country around Eungella Dam.

Petrocidae

The Australian robins are a large family but have only three representatives in the Eungella region: White-browed Robin (*Poecilodryas superciliosa*), Eastern Yellow Robin (*Eopsaltria australis chrysorrhoa*) and Jacky Winter (*Microeca fascinans fascinans*).

Alaudidae

A single lark, Horsfield's Bushlark (*Mirafra javanica horsfieldii*), occurs in the dry country to the west of Eungella.

Hirundinidae

The swallows and martins are represented in Eungella by three common species: Welcome Swallow (*Hirundo neoxena neoxena*), Fairy Martin (*Petrochelidon ariel*) and Tree Martin (*P. nigricans neglecta*).

Locustellidae

The Tawny Grassbird (*Megalurus timoriensis*) is the only member of this family to occur in the Eungella region, and can be seen singing in display flights above grassy areas in late spring and summer.

Cisticolidae

The Golden-headed Cisticola (*Cisticola exilis diminuta*) is the only member of this family to occur in the Eungella region.

Zosteropidae

The Silvereye (*Zosterops lateralis cornwallis*) is the only member of this family to occur in the Eungella region.

Sturnidae

There are potential historical records of Common Myna (*Acridotheres tristis*) occurring around Eungella, but we found little reliable information on the occurrence of the species in the region.

Turdidae

Only one thrush species occurs in the Eungella region: the Russet-tailed Thrush (*Zoothera heinei*). During the Eungella Biodiversity Survey, Russet-tailed Thrush was observed at sites at 400 m, 1000 m and 1200 m asl, and was recorded using automated acoustic recorders at 200 m, 400 m and 800 m asl sites. The lack of records at 600 m may be habitat-driven and mediated by fire: there is a band of wet sclerophyll forest running through the drier ridges of the 600 m contour line on the forested slopes of the mountains. Above this elevation, the rainforest is usually kept moist by a blanket of cloud; below this elevation, gullies and creeks trap moisture moving downslope. The occurrence of Russet-tailed Thrush above 1000 m in Eungella probably reflects the warmer climate at this latitude compared with that of the southern populations. In the Gondwanan Rainforests of the Queensland/New South Wales border, for example, Russet-tailed Thrush is generally restricted to elevations below 700 m (Leach, 2016).

Dicaeidae

The Mistletoebird (*Dicaeum hirundinaceum*) is the only member of this family to occur in the Eungella region, and may be found wherever mistletoes (Loranthaceae or Santalaceae spp.) are in flower.

Estrildidae

Four finches occur in the Eungella region, representing three genera: *Neochmia*, *Taeniopygia* and *Lonchura*. For subspecific and habitat information, see Table 1.

Motacillidae

The Australian Pipit (*Anthus australis*) is the only motacillid to occur in Eungella, though vagrant motacillids, such as the Eastern Yellow Wagtail (*Motacilla tschutschensis*), may go undetected in the region due to a relative lack of survey effort.

TABLE 1. The birds of Eungella in taxonomic order, including notes on elevational distribution in Eungella National Park if recorded during the Eungella Biodiversity Survey, and notes on habitat, distribution and likelihood of occurrence within the broader region. Taxonomy follows IOC Checklist v 9.1 (Gill & Donsker, 2019).

Scientific name	IOC English name	Elevational distribution	Notes
Casuariiformes			
Dromaiidae	**Emu**		
Dromaius novaehollandiae	Emu		Potential in dry country around Eungella Dam
Anseriformes			
Anseranatidae	**Magpie Goose**		
Anseranas semipalmata	Magpie Goose		Wetlands, paddocks
Anatidae	**Ducks, Geese & Swans**		
Dendrocygna eytoni	Plumed Whistling Duck		Wetlands, farm dams
Dendrocygna arcuata	Wandering Whistling Duck		Wetlands, farm dams
Cygnus atratus	Black Swan		Wetlands, Eungella Dam
Tadorna radjah rufitergum	Raja Shelduck		Wetlands; uncommon
Chenonetta jubata	Maned Duck		Wetlands, paddocks; common
Nettapus coromandelianus	Cotton Pygmy Goose		Eungella Dam
Nettapus pulchellus	Green Pygmy Goose		Eungella Dam
Anas superciliosa	Pacific Black Duck		Wetlands, farm dams
Anas gracilis	Grey Teal		Wetlands, Eungella Dam
Aythya australis	Hardhead		Eungella Dam, farm dams
Galliformes			
Megapodiidae	**Megapodes**		
Alectura lathami lathami	Australian Brushturkey	200 m–400 m	Occasionally seen in forest
Megapodius reinwardt tumulus	Orange-footed Scrubfowl	200 m–400 m	More often heard than seen
Phasianidae	**Pheasants, Fowl & Allies**		
Coturnix pectoralis	Stubble Quail		Irruptive
Coturnix ypsilophora	Brown Quail		Rank grass
Excalfactoria chinensis victoriae	King Quail		Irruptive
Podicipediformes			
Podicipedidae	**Grebes**		
Tachybaptus novaehollandiae	Australasian Grebe		Eungella Dam, farm dams
Poliocephalus poliocephalus	Hoary-headed Grebe		Eungella Dam, farm dams
Podiceps cristatus	Great Crested Grebe		Eungella Dam, farm dams
Ciconiiformes			
Ciconiidae	**Storks**		
Ephippiorhynchus asiaticus	Black-necked Stork		Occasional in paddocks and around Eungella Dam

Scientific name	IOC English name	Elevational distribution	Notes
Pelecaniformes			
Threskiornithidae	**Ibises, Spoonbills**		
Threskiornis moluccus	Australian White Ibis		Eungella Dam, farm dams, paddocks
Threskiornis spinicollis	Straw-necked Ibis		Eungella Dam, farm dams, paddocks
Plegadis falcinellus	Glossy Ibis		Eungella Dam, farm dams, paddocks
Platalea regia	Royal Spoonbill		Eungella Dam, farm dams
Platalea flavipes	Yellow-billed Spoonbill		Eungella Dam, farm dams
Ardeidae	**Herons, Bitterns**		
Nycticorax caledonicus	Nankeen Night Heron		Creeklines
Bubulcus coromandus	Eastern Cattle Egret		Paddocks, grasslands with cattle
Ardea pacifica	White-necked Heron		Farm dams and swamps
Ardea alba	Great Egret		Eungella Dam, farm dams
Egretta intermedia	Intermediate Egret		Eungella Dam, farm dams
Egretta novaehollandiae	White-faced Heron		Eungella Dam, farm dams
Egretta garzetta	Little Egret		Eungella Dam, farm dams
Pelecanidae	**Pelicans**		
Pelecanus conspicillatus	Australian Pelican		Eungella Dam
Phalacrocoracidae	**Cormorants, shags**		
Microcarbo melanoleucos	Little Pied Cormorant	200 m	Eungella Dam, Owens Creek, Finch Hatton Gorge
Phalacrocorax sulcirostris	Little Black Cormorant	200 m	Eungella Dam, Owens Creek, Finch Hatton Gorge
Phalacrocorax varius	Australian Pied Cormorant		Eungella Dam
Phalacrocorax carbo	Great Cormorant		Eungella Dam
Anhingidae	**Anhingas, darters**		
Anhinga novaehollandiae	Australasian Darter		Eungella Dam
Accipitriformes			
Pandionidae	**Ospreys**		
Pandion cristatus	Eastern Osprey	200 m	Owens Creek (occasional), Pioneer Valley
Accipitridae	**Kites, Hawks & Eagles**		
Elanus axillaris	Black-shouldered Kite		Open country, paddocks and farmland
Lophoictinia isura	Square-tailed Kite		Eucalypt forests (e.g. Crediton)
Aquila audax	Wedge-tailed Eagle	All elevations	Sometimes seen soaring above canopy
Accipiter novaehollandiae	Grey Goshawk	All elevations	Occasionally seen in forest

Scientific name	**IOC English name**	**Elevational distribution**	**Notes**
***Accipitriformes* (cont.)**			
Pandionidae	**Ospreys**		
Accipiter fasciatus fasciatus	Brown Goshawk		Rainforest fringe, eucalypt forest
Accipiter cirrocephalus	Collared Sparrowhawk	200 m	Once seen along Owens Creek but probably occurs at all elevations
Circus approximans	Swamp Harrier		Farmlands, especially associated with water bodies
Circus assimilis	Spotted Harrier		Farmlands, grassy areas
Milvus migrans	Black Kite		Dry country to the west of Eungella
Haliastur sphenurus	Whistling Kite		Occasionally recorded in Pioneer Valley
Haliastur indus	Brahminy Kite		Occasionally recorded in Pioneer Valley; once seen along Owens Creek
Haliaeetus leucogaster	White-bellied Sea Eagle		Eungella Dam, upper Pioneer Valley
Otidiformes			
Otididae	**Bustards**		
Ardeotis australis	Australian Bustard		Dry country around Eungella Dam
Gruiformes			
Rallidae	**Rails, Crakes & Coots**		
Gallirallus philippensis mellori	Buff-banded Rail		Rank vegetation, creeklines and farm dams
Amaurornis moluccana	Pale-vented Bush-hen		Rank vegetation, creeklines at lower elevations
Porzana pusilla	Baillon's Crake		Occasionally recorded at Eungella Dam
Porphyrio porphyrio melanotus	Purple Swamphen		Wetlands, farm dams
Gallinula tenebrosa	Dusky Moorhen		Wetlands, farm dams
Tribonyx ventralis	Black-tailed Nativehen		Wetlands, farm dams
Fulica atra	Eurasian Coot		Eungella Dam
Gruidae	**Cranes**		
Grus rubicunda	Brolga		Farmlands, grasslands
Charadriiformes			
Turnicidae	**Buttonquail**		
Turnix maculosus	Red-backed Buttonquail		Irruptive
Turnix varius	Painted Buttonquail		Irruptive
Turnix pyrrhothorax	Red-chested Buttonquail		Irruptive
Turnix velox	Little Buttonquail		Irruptive

Scientific name	IOC English name	Elevational distribution	Notes
***Charadriiformes* (cont.)**			
Burhinidae	**Stone-curlews**		
Burhinus grallarius	Bush Stone-curlew		Occasionally recorded in Pioneer Valley
Recurvirostridae	**Stilts, Avocets**		
Himantopus leucocephalus	White-headed Stilt		Farm dams and watercourses
Charadriidae	**Plovers**		
Vanellus tricolor	Banded Lapwing		Dry country grasslands
Vanellus miles miles / novaehollandiae	Masked/Black-shouldered Lapwing		Grasslands, farmlands
Erythrogonys cinctus	Red-kneed Dotterel		Eungella Dam, farm dams
Elseyornis melanops	Black-fronted Dotterel		Eungella Dam, farm dams
Scolopacidae	**Sandpipers, Snipes**		
Gallinago hardwickii	Latham's Snipe		Farm dams, swamps and watercourses
Laridae	**Gulls, Terns & Skimmers**		
Chroicocephalus novaehollandiae	**Silver Gull**		Eungella Dam
Gelochelidon nilotica	Gull-billed Tern		Eungella Dam
Hydroprogne caspia	Caspian Tern		Eungella Dam
Chlidonias hybrida	Whiskered Tern		Eungella Dam
Columbiformes			
Columbidae	**Pigeons, Doves**		
Columba livia	Rock Dove		Towns
Columba leucomela	White-headed Pigeon	800 m–1200 m	Prefers higher elevation rainforest; uncommon
Spilopelia chinensis	Spotted Dove		Towns
Macropygia phasianella robinsoni	Brown Cuckoo-Dove	All elevations	Common in rainforest
Chalcophaps longirostris chrysochlora	Pacific Emerald Dove	800 m	Uncommon at most elevations; relatively common around Sky Window
Phaps chalcoptera	Common Bronzewing		Occurs in dry eucalypt forest (e.g. Crediton)
Ocyphaps lophotes lophotes	Crested Pigeon		Farmlands, grasslands
Geophaps scripta scripta	Squatter Pigeon		Dry country around Eungella Dam
Geopelia cuneata	Diamond Dove		Dry country around Eungella Dam
Geopelia placida placida	Peaceful Dove		Dry country around Eungella Dam, towns
Geopelia humeralis humeralis	Bar-shouldered Dove	200 m	Finch Hatton Gorge, dry eucalypt forest

Scientific name	IOC English name	Elevational distribution	Notes
***Columbiformes* (cont.)**			
Columbidae	**Pigeons, Doves**		
Ptilinopus magnificus keri	Wompoo Fruit Dove	All elevations	Common in rainforest
Ptilinopus superbus	Superb Fruit Dove	All elevations	Common in rainforest
Ptilinopus regina regina	Rose-crowned Fruit Dove	All elevations	Fairly common in rainforest
Ducula spilorrhoa	Torresian Imperial Pigeon	200 m–400 m	Summer migrant; common around Finch Hatton
Lopholaimus antarcticus	Topknot Pigeon	400 m–1200 m	Prefers higher elevation rainforest (>800 m)
Cuculiformes			
Cuculidae	**Cuckoos**		
Centropus phasianinus phasianinus	Pheasant Coucal		Rank vegetation, creeklines at lower elevations
Eudynamys orientalis subcyanocephala	Pacific Koel	200 m	Summer migrant; prefers lower elevations
Scythrops novaehollandiae	Channel-billed Cuckoo		Summer migrant; occurs near nesting areas of hosts
Chrysococcyx basalis	Horsfield's Bronze Cuckoo		Dry country, paddocks and farm dams
Chrysococcyx osculans	Black-eared Cuckoo		Dry country around Eungella Dam
Chrysococcyx lucidus	Shining Bronze Cuckoo	400 m–1200 m	Common in rainforest
Chrysococcyx minutillus minutillus / russatus	Little/Gould's Bronze Cuckoo		Potential to occur in most forested habitats, particularly near water
Cacomantis pallidus	Pallid Cuckoo		Dry country around Eungella Dam and further west
Cacomantis flabelliformis	Fan-tailed Cuckoo	All elevations	Common in rainforest
Cacomantis variolosus	Brush Cuckoo		Eucalypt forests (e.g. Crediton)
Cuculus optatus	Oriental Cuckoo		Occasional visitor; summer migrant
Strigiformes			
Tytonidae	**Barn Owls**		
Tyto tenebricosa	Greater Sooty Owl	200 m, 1000 m	Survey records at 200 m and 1000 m but probably occurs at all elevations; uncommon
Tyto delicatula	Eastern Barn Owl	800 m, 1000 m	Recorded on forest verge along road
Strigidae	**Owls**		
Ninox rufa queenslandica	Rufous Owl		Creeklines and gallery forest
Ninox strenua	Powerful Owl		Eucalypt forests
Ninox connivens connivens	Barking Owl		Rare
Ninox boobook boobook	Southern Boobook	200 m–1200 m	Forested habitats; fairly common in rainforest

Scientific name	IOC English name	Elevational distribution	Notes
Caprimulgiformes			
Podargidae	**Frogmouths**		
Podargus strigoides strigoides	Tawny Frogmouth		Fairly common
Caprimulgidae	**Nightjars**		
Eurostopodus argus	Spotted Nightjar		More easily detected by call; may be seen resting on roads and tracks at night; most likely to the west of Eungella village
Eurostopodus mystacalis	White-throated Nightjar		More easily detected by call; may be seen resting on roads and tracks at night
Caprimulgus macrurus	Large-tailed Nightjar		More easily detected by call; may be seen resting on roads and tracks at night
Apodiformes			
Aegothelidae	**Owlet-nightjars**		
Aegotheles cristatus	Australian Owlet-nightjar		Fairly common in most habitats with hollow-bearing trees
Apodidae	**Swifts**		
Aerodramus terraereginae terraereginae	Australian Swiftlet	200 m, 1200 m	Common over canefields in Pioneer Valley; breeds in caves in Finch Hatton Gorge
Hirundapus caudacutus	White-throated Needletail	1000 m, 1200 m	May occur overhead spring–summer
Apus pacificus	Pacific Swift		May occur overhead spring–summer
Coraciiformes			
Coraciidae	**Rollers**		
Eurystomus orientalis	Oriental Dollarbird		Summer migrant; often perches on exposed branches or telephone wires
Alcedinidae	**Kingfishers**		
Tanysiptera sylvia	Buff-breasted Paradise Kingfisher	200 m–600 m	Breeding migrant; nests in terrestrial termite mounds at low elevations
Dacelo novaeguineae	Laughing Kookaburra	All elevations	Common in open habitats; also occurs in rainforest
Dacelo leachii	Blue-winged Kookaburra		Dry country around Eungella Dam and further west
Todiramphus macleayii incinctus	Forest Kingfisher		Common
Todiramphus sanctus sanctus	Sacred Kingfisher		Open country, eucalypt forest
Todiramphus pyrrhopygius	Red-backed Kingfisher		Dry country around Eungella Dam and further west
Ceyx azureus azureus	Azure Kingfisher	200 m–1200 m	Creeklines

Scientific name	**IOC English name**	**Elevational distribution**	**Notes**
***Coraciiformes* (cont.)**			
Meropidae	**Bee-eaters**		
Merops ornatus	Rainbow Bee-eater	600 m	Occasionally above rainforest canopy; common elsewhere in suitable habitat
Falconiformes			
Falconidae	**Caracaras, Falcons**		
Falco cenchroides	Nankeen Kestrel		Paddocks, grassland
Falco longipennis	Australian Hobby		Grasslands, margins of lakes and forests
Falco berigora	Brown Falcon		Most open habitats
Falco peregrinus	Peregrine Falcon		Occasional; sometimes seen from summit of Mt Dalrymple
Psittaciformes			
Cacatuidae	**Cockatoos**		
Calyptorhynchus banksii banksii	Red-tailed Black Cockatoo	All elevations	Large flock often flies over the Clarke Range in the morning and afternoon
Calyptorhynchus lathami erebus	Glossy Black Cockatoo		Rare visitor to the region
Calyptorhynchus funereus funereus	Yellow-tailed Black Cockatoo		Rare visitor to the region
Eolophus roseicapilla kuhli / albiceps	Galah		Common around towns and open country
Cacatua sanguinea gymnopsis	Little Corella		Towns
Cacatua galerita galerita	Sulphur-crested Cockatoo	400 m–1200 m	Common
Nymphicus hollandicus	Cockatiel		Dry country to the west of Eungella
Psittacidae	**Parrots**		
Trichoglossus moluccanus moluccanus	Rainbow Lorikeet	600 m	In the rainforest, only occur in association with the eucalypt band at 600 m; uncommon
Trichoglossus chlorolepidotus	Scaly-breasted Lorikeet		Possible at flowering eucalypts
Glossopsitta pusilla	Little Lorikeet		Possible at flowering eucalypts
Platycercus elegans	Crimson Rosella	800 m, 1000 m	Infrequently seen in rainforest
Platycercus adscitus	Pale-headed Rosella		Possible in sclerophyll forest
Alisterus scapularis	Australian King Parrot	200 m, 400 m, 600 m, 1000 m	Common in rainforest
Aprosmictus erythropterus	Red-winged Parrot		Dry country to the west of Eungella
Passeriformes			
Pittidae	**Pittas**		
Pitta versicolor intermedia	Noisy Pitta	All elevations	Common

Scientific name	IOC English name	Elevational distribution	Notes
Passeriformes (cont.)			
Ptilonorhynchidae	**Bowerbirds**		
Sericulus chrysocephalus	Regent Bowerbird	1000 m, 1200 m	Restricted to high-elevation rainforest
Chlamydera nuchalis orientalis	Great Bowerbird		Dry country to the west of Eungella
Climacteridae	**Australasian Treecreepers**		
Cormobates leucophaea intermedia	White-throated Treecreeper	All elevations	Fairly common in rainforest
Maluridae	**Australasian Wrens**		
Malurus melanocephalus melnocephalus	Red-backed Fairywren		Scrubby and grassy habitat
Meliphagidae	**Honeyeaters**		
Myzomela obscura harteri	Dusky Myzomela		Eungella village and surrounds
Myzomela sanguinolenta	Scarlet Myzomela	200 m–800 m	Blossom migrant
Acanthorhynchus tenuirostris tenuirostris	Eastern Spinebill	400 m, 800 m, 1200 m	Probably occurs at all elevations
Lichmera indistincta ocularis	Brown Honeyeater		Creeklines and eucalypt forests
Phylidonyris niger niger	White-cheeked Honeyeater		Isolated population; northernmost limit
Philemon citreogularis citreogularis	Little Friarbird		Possible in sclerophyll forest
Philemon yorki	Hornbill Friarbird		Occurs around Eungella Dam
Philemon corniculatus corniculatus	Noisy Friarbird	600 m	Occurs in eucalyptus band in the rainforest
Entomyzon cyanotis cyanotis	Blue-faced Honeyeater		Eucalypt forests
Melithreptus gularis gularis / laetior	Black-chinned Honeyeater		Subspecific hybrids may occur
Melithreptus albogularis inopinatus	White-throated Honeyeater		Eucalypt forests
Melithreptus lunatus	White-naped Honeyeater		Eucalypt forests (prefers wetter habitats)
Ramsayornis fasciatus	Bar-breasted Honeyeater		Small number of records from Broken River
Bolemoreus hindwoodi	Eungella Honeyeater	400 m, 800–1200 m	Seen only once at 400 m; common above 800 m
Caligavis chrysops barroni	Yellow-faced Honeyeater		Eucalypt forests, high elevations
Manorina melanocephala lepidota	Noisy Miner		Eucalypt forests (e.g. Crediton)
Manorina flavigula flavigula	Yellow-throated Miner		Occurs around Eungella Dam and further west
Stomiopera flava addendus	Yellow Honeyeater		Eucalypt forest, rainforest margins, creeklines

Scientific name	**IOC English name**	**Elevational distribution**	**Notes**
Passeriformes **(cont.)**			
Meliphagidae	**Honeyeaters**		
Meliphaga lewinii mab	Lewin's Honeyeater	All elevations	Scarce above 1000 m, where Eungella Honeyeater might outcompete; common elsewhere
Pardalotidae	**Pardalotes**		
Pardalotus punctatus punctatus	Spotted Pardalote	400 m, 600 m	Associated with wet sclerophyll band
Pardalotus striatus melanocephalus	Striated Pardalote		Most common in eucalypt forest and scrub
Acanthizidae	**Australasian Warblers**		
Sericornis frontalis laevigaster	White-browed Scrubwren	All elevations	Common
Sericornis magnirostra magnirostra	Large-billed Scrubwren	All elevations	Most common around 400 m
Smicrornis brevirostris brevirostris	Weebill		Dry country to the west of Eungella
Gerygone mouki amalia	Brown Gerygone		Common, particularly above 800 m
Gerygone magnirostris cairnsensis	Large-billed Gerygone		Uncommon; occurs around creeklines in Pioneer Valley
Gerygone olivacea olivacea	White-throated Gerygone		Eucalypt forests (e.g. Crediton)
Gerygone palpebrosa flavida	Fairy Gerygone	200 m, 400 m, 600 m	Uncommon
Acanthiza pusilla dawsonensis	Brown Thornbill	All elevations	Common
Acanthiza reguloides squamata	Buff-rumped Thornbill		Eucalypt forests
Acanthiza nana modesta	Yellow Thornbill		Eucalypt forests
Psophodidae	**Whipbirds, Quail-thrushes**		
Psophodes olivaceus olivaceous	Eastern Whipbird	All elevations	Common
Artamidae	**Woodswallows, Butcherbirds and allies**		
Artamus leucorynchus	White-breasted Woodswallow		Open country, towns, farms
Artamus personatus	Masked Woodswallow		Vagrant; associated with dry country to the west
Artamus superciliosus	White-browed Woodswallow		Vagrant; associated with dry country to the west
Artamus cinereus	Black-faced Woodswallow		Vagrant; associated with dry country to the west
Artamus cyanopterus	Dusky Woodswallow		Vagrant; associated with dry country to the west
Cracticus quoyi rufescens	Black Butcherbird	All elevations except 800 m	Uncommon in rainforest
Cracticus torquatus torquatus	Grey Butcherbird		Open country, towns, farms
Cracticus nigrogularis nigrogularis	Pied Butcherbird		Open country, towns, farms

Scientific name	IOC English name	Elevational distribution	Notes
***Passeriformes* (cont.)**			
Artamidae	**Woodswallows, Butcherbirds and allies**		
Gymnorhina tibicen	Australian Magpie		Open country, towns, farms
Strepera graculina graculina	Pied Currawong	All elevations except 200 m	Common in rainforest
Campephagidae	**Cuckooshrikes**		
Coracina novaehollandiae melanops	Black-faced Cuckooshrike		Eucalypt forests, open country
Coracina lineata	Barred Cuckooshrike	200 m	Creeklines; Finch Hatton Gorge and Owens Creek
Coracina papuensis artamoides	White-bellied Cuckooshrike		Dry country around Eungella Dam and further west
Coracina tenuirostris tenuirostris	Common Cicadabird	All elevations except 1000 m	Mainly seen, not heard; uncommon
Lalage tricolor	White-winged Triller		Dry country to the west of Eungella
Lalage leucomela leucomela	Varied Triller	400 m, 600 m	Most frequent at 400 m, but not commonly encountered
Neosittidae	**Sittellas**		
Daphoenositta chrysoptera leucocephala	Varied Sittella		Subspecies *striata* also has the potential to occur in the region
Pachycephalidae	**Whistlers and Allies**		
Pachycephala pectoralis pectoralis	Australian Golden Whistler	200 m, 800 m–1200 m	Only seen once at 200 m; most common above 1000 m
Pachycephala rufiventris rufiventris	Rufous Whistler		Eucalypt forest, rainforest margins
Colluricincla megarhyncha synaptica	Little Shrikethrush	200 m–800 m	Most common below 600 m
Colluricincla harmonica harmonica	Grey Shrikethrush	800 m–1200 m	Uncommon
Oriolidae	**Figbirds, Orioles**		
Sphecotheres vieilloti vieilloti	Australasian Figbird	800 m, 1000 m	Only seen twice in rainforest
Oriolus sagittatus sagittatus	Olive-backed Oriole		Eucalypt forest, rainforest margins, creeklines
Dicruridae	**Drongos**		
Dicrurus bracteatus bracteatus	Spangled Drongo		Fairly common in eucalypt forest and rainforest margins
Rhipiduridae	**Fantails**		
Rhipidura leucophrys leucophrys	Willie Wagtail		Open country
Rhipidura albiscapa keasti	Grey Fantail	All elevations	Common
Rhipidura rufifrons intermedia	Rufous Fantail	All elevations	Uncommon

Scientific name	**IOC English name**	**Elevational distribution**	**Notes**
***Passeriformes* (cont.)**			
Monarchidae	**Monarchs**		
Symposiachrus trivirgatus melanorrhoa	Spectacled Monarch	200 m–800 m	Common
Monarcha melanopsis	Black-faced Monarch	200 m–1000 m	Only recorded once at 1000 m; common at lower elevations
Carterornis leucotis	White-eared Monarch	200 m–600 m	Uncommon
Grallina cyanoleuca cyanoleuca	Magpie-lark		Open country, towns, farms
Myiagra rubecula yorki	Leaden Flycatcher		Eucalypt forest, rainforest margins
Myiagra inquieta	Restless Flycatcher		Eucalypt forests (e.g. Crediton)
Corvidae	**Crows, Jays**		
Corvus orru	Torresian Crow		Open country, towns, farms
Corvus coronoides	Australian Raven		Old records from Eungella village
Corcoracidae	**Australian Mudnesters**		
Corcorax melanorhamphos melanorhamphos	White-winged Chough		Dry eucalypt forest
Struthidea cinerea dalyi	Apostlebird		Dry country to the west of Eungella
Petroicidae	**Australasian Robins**		
Poecilodryas superciliosa	White-browed Robin		Records from upper Pioneer Valley and eastern slopes
Eopsaltria australis chryshorrhoa	Eastern Yellow Robin	All elevations	Common
Microeca fascinans fascinans	Jacky Winter		Dry country to the west of Eungella
Alaudidae	**Larks**		
Mirafra javanica horsfieldii	Horsfield's Bush Lark		Dry country to the west of Eungella; Lizzie Creek Road
Hirundinidae	**Swallows, Martins**		
Hirundo neoxena neoxena	Welcome Swallow		Common
Petrochelidon ariel	Fairy Martin		Common
Petrochelidon nigricans neglecta	Tree Martin		Common
Locustellidae	**Grassbirds and allies**		
Megalurus timoriensis	Tawny Grassbird		Wetlands, rank grassland
Cisticolidae	**Cisticolas and allies**		
Cisticola exilis diminuta	Golden-headed Cisticola		Wetlands, rank grassland
Zosteropidae	**White-eyes**		
Zosterops lateralis cornwallis	Silvereye	All elevations	Common

Scientific name	IOC English name	Elevational distribution	Notes
Passeriformes (cont.)			
Sturnidae	**Starlings**		
Acridotheres tristis	Common Myna		Introduced and invasive; some recent records from Eungella, but appears not to have become established
Turdidae	**Thrushes**		
Zoothera heinei	Russet-tailed Thrush	All elevations	Uncommon; mostly detected using acoustic recorders; seen occasionally around 1000 m
Dicaeidae	**Flowerpeckers**		
Dicaeum hirundinaceum	Mistletoebird		Could occur anywhere with flowering mistletoes
Passeridae	**Old World Sparrows**		
Passer domesticus	House Sparrow		Towns
Estrildidae	**Waxbills, Munias & Allies**		
Neochmia temporalis temporalis	Red-browed Finch		Common in grasslands
Taeniopygia guttata	**Zebra Finch**		More likely to occur to the west of Eungella village
Taeniopygia bichenovii bichenovii	Double-barred Finch		Grasslands; often near water
Lonchura castaneothorax	Chestnut-breasted Mannikin		Grasslands; often near water
Motacillidae	**Wagtails, Pipits**		
Anthus australis	Australian Pipit		Paddocks, open country

CONCLUSIONS

The effects of the biogeographic barriers to the north and south on the flora and fauna of ENP are clearly evident. The upland rainforest contains many subtropical plant species despite Eungella's location well north of the Tropic of Capricorn (Ashton *et al.*, 2019), and the avian community of the region is also made up of a combination of tropical and subtropical species. For example, the tropical Black Butcherbird (*Cracticus quoyi rufescens*), Buff-breasted Paradise Kingfisher (*Tanysiptera sylvia*) and Orange-footed Scrubfowl (*Megapodius reinwardt tumulus*) are all close to the southern limit of their distributions in the Eungella region and typically inhabit the warm, humid rainforests of the lowlands. These species occur in the same area as small populations of Regent Bowerbird (*Sericulus chrysocephalus*), Russet-tailed Thrush (*Zoothera heinei*) and Greater Sooty Owl (*Tyto tenebricosa*) – all subtropical species at the extreme northern limits of their distribution, and all essentially restricted to the cool, cloudy upland rainforest of ENP. These latter species effectively occupy tolerable cool 'islands' in a warmer 'sea' of unsuitable habitat and, accordingly, should be regarded as threatened by ongoing climatic change (Anderson, 2011; Shoo *et al.*, 2005).

Given the overlap between tropical and subtropical fauna and flora in Eungella, there are some surprising bird species that are absent from the region. Riflebirds, catbirds and logrunners have representative species to the north of the Eungella region: Victoria's Riflebird (*Ptiloris victoriae*), Spotted Catbird (*Ailuroedus melanotis*) and Chowchilla (*Orthonyx spaldingii*) are all endemic to the Wet Tropics. To the south, Paradise Riflebird (*P. paradiseus*), Green Catbird (*A. crassirostris*) and Australian Logrunner (*O. temminckii*) occupy the subtropical Gondwanan Rainforests. Despite this, there are no representative species belonging to these groups in the Eungella region. This pattern is also evident at the subspecific level: one example is of the Yellow-throated Scrubwren (*Sericornis citreogularis*), which is absent from the Eungella region but has subspecific representatives in the Wet Tropics (*S. c. cairnsi*) and the Gondwanan Rainforests (*S. c. intermedia*). Whether or not these patterns in distribution can be linked to the historical biogeographical isolation of the central Queensland rainforests and/or extinction debt remains speculative; it is difficult to determine why these groups and subspecies, in particular, are absent from the region.

Such absences are offset by the presence of numerous endemic species and subspecies belonging to many faunal groups in the Eungella region. Perhaps the most famous endemic bird in the region, the Eungella Honeyeater (*Bolemoreus hindwoodi*) was only recognised as a distinct species in 1983, when it was split from the closely related Bridled Honeyeater (*B. frenatus*) of the Wet Tropics (Longmore & Boles, 1983). Similarly, Boles & Longmore (1983) described a novel subspecies in the White-throated Treecreeper complex, *Cormobates leucophaea intermedia*, that is restricted to the Clarke and Connors Ranges. Additionally, there are endemic frog, reptile and invertebrate species that occur in the region (see other contributions in this volume). The unique biodiversity of the Eungella region, like that of many other mountain refugia on the east coast of Australia, is seriously threatened by ongoing climatic change (Williams *et al*., 2003). Ongoing warming in the study region is predicted to lead to average mean temperatures 0.4 to 1.3°C above the climate of 1986–2005 by 2030 (CSIRO and Bureau of Meteorology, 2015). By late in the century (2090), under a high-emissions scenario, the average increase in mean temperatures could be 2.5 to 5.0°C (CSIRO and Bureau of Meteorology, 2015). For the Eungella Honeyeater, as well as species currently at the northern limit of their distributions (e.g. Regent Bowerbird), warming of this magnitude is almost certain to lead to local extinction (Anderson, 2011; Leach, 2017). It is imperative that we gain a better understanding of the distributions, elevational preferences and environmental tolerances of Australian birds if we are to predict and manage the impacts of climate change on their populations effectively.

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THE EXTENT AND SEVERITY OF THE MACKAY HIGHLANDS 2018 WILDFIRES AND THE POTENTIAL IMPACT ON NATURAL VALUES, PARTICULARLY IN THE MESIC FORESTS OF THE EUNGELLA-CREDITON AREA

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During an unprecedented fire season in Queensland in 2018, a complex of fires burnt in the Mackay Highlands region of Queensland. Some of these fires had been burning continuously since August, but an extreme heatwave in November caused the rapid expansion of intense fire, just prior to the wet season breaking. The fires affected 12 areas of Queensland Parks and Wildlife Service (QPWS) managed estate, with approximately 71,000 ha or 41% of this estate burnt. In this paper, we document the methods used to map the extent and severity of these fires and consider the potential impacts on natural values, within QPWS managed estate. Extensive areas (57,113 ha) of eucalypt woodlands and forests were burnt. Whilst fire adapted, the extent of fire and the high proportion burnt at very high to extreme severity in these ecosystems are likely to have affected a range of significant species. Of particular concern was the area (11,217 ha) of rainforest and scrub communities burnt, particularly cloud rainforests in the Eungella-Crediton area. These are highly fire-sensitive ecosystems and our observations suggest that, even at very low fire severity, impacts are likely highly significant and long lasting. This event provides an important opportunity to assess in detail the ecological effects of fire to inform conservation management of these fire-sensitive communities. With the predicted increases in the frequency, magnitude and duration of heatwaves, fires will become more common within mesic vegetation communities hitherto considered self-protected from fire.

Keywords: Mackay Highlands, Eungella, fire, severity, ecological impact, rainforest

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INTRODUCTION

The 2018 fire season in Queensland was unprecedented. The fire-weather conditions (extreme temperatures, low humidity and strong westerly winds, coupled with preceding dry conditions), particularly during November 2018, led to fire behaviour at an intensity and scale never before seen in the State. This included a catastrophic fire-weather day on 28 November 2018 (BoM, 2018; QFES, 2019).

The extensive Mackay Highlands 2018 wildfire event comprised multiple fires, some burning continuously from August, that culminated with a rapid expansion of intense fire in mid–late November fuelled by extreme fire-weather conditions. Of particular conservation management and ecological significance, the Mackay Highlands fires burnt fire-sensitive upland rainforest, including cloud rainforests, generally regarded as self-protected from fire due to their occurrence on rocky substrates, moist microclimate, or both. Fires were also extensive and at times severe in eucalypt fire-adapted communities.

Here, we summarise the climatic conditions leading up to and during the fire event, describe the extent and severity of the burnt area, document significant species and ecosystems within the burnt area, and discuss possible ecological effects on them. We focus on the significant natural values of the rainforest and scrubs, and wet eucalypt open forest communities of the Eungella-Crediton area.

MATERIALS AND METHODS

Study Area

This paper reports on the fires that burnt along the Great Escarpment of eastern Australia, from the Mount Hector–Bloomsbury area in the north, to the Blue Mountains area west of Koumala in the south (Figure 1). The major landscape features in this region are the uplands of the Clarke, Connors, Denham, Blue Mountains and Pisgah Ranges, which include many peaks in excess of 700 m altitude. The peaks of Mts David, Dalrymple and William on the Clarke Range within Eungella National Park (NP) rise to above 1200 m in altitude. The region also includes the spectacular formations of Diamond Cliffs, Sydney Heads, The Marling Spikes and Mount Britton in Homevale NP and Resources Reserve (RR). Landforms vary from rolling hills to steeply dissected mountains and valleys. The western slopes of the area drain predominantly into the headwaters of the Burdekin River, with southern areas draining into the headwaters of the Fitzroy River. Many short streams drain the eastern escarpment, including the Pioneer and O'Connell Rivers.

Much of the burnt area falls within the Clarke-Connors Ranges Province of the Central Queensland Coast Bioregion (Young, 1999) which is predominantly subcoastal ranges and uplands, with the highest, moistest parts of the bioregion, generally with a steep eastern fall. Geology is predominantly Carboniferous-Mesozoic granite, diorite, granodiorite, but also Permian volcanics. Vegetation is dominated by notophyll rainforest, *Eucalyptus* open forest and tall open forest. Most of Homevale NP and RR and the western part of Eungella NP fall in the lower-altitude, much drier Bogie River Hills Province of the Brigalow Belt Bioregion. Vegetation in these areas is dominated by open *Eucalyptus* and *Corymbia* woodlands with scattered vine thickets (Young *et al.*, 1999).

Climatically, the area of interest typically has marked wet summers and dry winters with median rainfall in excess of 650 mm (BoM, 2019), with upland areas very much moister due to orographic and cloud-stripping effects. Lower areas fall within the hot humid summer climate zone, with elevated areas falling within the warm humid summer or warm summer, cold winter climate zone (BoM, 2019).

Weather Conditions Leading Up to and During the Fire Event

The fire season in the Mackay Highlands area typically comprises the drier months from May to November. The latter part of the 2018 fire season was exceptional, with an extreme heatwave developing during late November. A deep low to the east of southern New South Wales directed a hot and dry westerly airflow across Queensland. Persistent, high to extreme daytime temperatures, combined with very high overnight temperatures and low humidity, created a broad-scale severe to extreme heatwave over and near the tropical Queensland coast from 23 November (BoM, 2018; QFES, 2019). The monthly mean temperature in Mackay for November 2018 surpassed the long-term average mean (29.6°C) by almost 3°C (at 32.5°C), equalling the highest monthly mean on record at 32.5°C (Mackay Aerodrome 1950–2018, BoM climate data online). The average mean temperature for each other month of 2018 exceeded the long-term mean by 0.2°C to 3°C (Figure 2). Compounding higher temperatures, monthly total rainfall for Mackay was below average for each month of 2018 except for April with 166.2 mm, just 2 mm above the long-term average.

For the cloud rainforests of the Eungella-Crediton area, dry conditions were likely significantly exacerbated by the lack of occult precipitation (precipitation that does not get recorded in standard rain gauges, from deposition of cloud, fog or drizzle water onto vegetation, sometimes referred to as cloud stripping: Bruijnzeel, 2001; Holwerda *et al.*, 2010) during this period. Typically, these areas are subject to moist afternoon sea breezes that result in cloud or fog forming and sitting on the mountains and escarpment, but this did not occur due to the dry westerly airflow. This not only reduces moisture reaching the forest floor via cloud stripping, but the increase in solar energy accelerates the hydrological cycle and increases evapotranspiration (Cardenas *et al.*, 2017), causing further drying of the forest. Temporal and spatial limitations of weather data for the Mackay highlands precludes more specific analyses of climatic conditions leading up to and during the event, especially for upland rainforests. The arrival of the wet season during the first week of December 2018 suppressed the fires.

Assessment Methodology

Given the extent and severity of the Mackay Highlands fires within Queensland Parks and Wildlife Service (QPWS) managed estate, QPWS undertook a post-fire risk assessment, in more detail than standard for the organisation (Brooke *et al.*, 2019). The methods used were modified from those of the Victorian *Bushfire Rapid Risk Assessment Teams* (e.g. DSE, 2009; DEPI, 2014, Case Study 4) and the New South Wales Parks and Wildlife Service and Australian Capital Territory Parks and Conservation *Burned Area Assessment Teams* (BAAT, 2013). The assessment provides QPWS with a snapshot of the priority risks to values, following the fires, to guide short-term responses and to inform long-term recovery planning. Only impacts on natural values are reported here, with the fire event recognised as also having social, cultural and economic consequences.

FIGURE 1. Map of the Mackay Highlands area, showing areas of QPWS estate and NAFI 2018 fire scar mapping. Base map: QTopo.

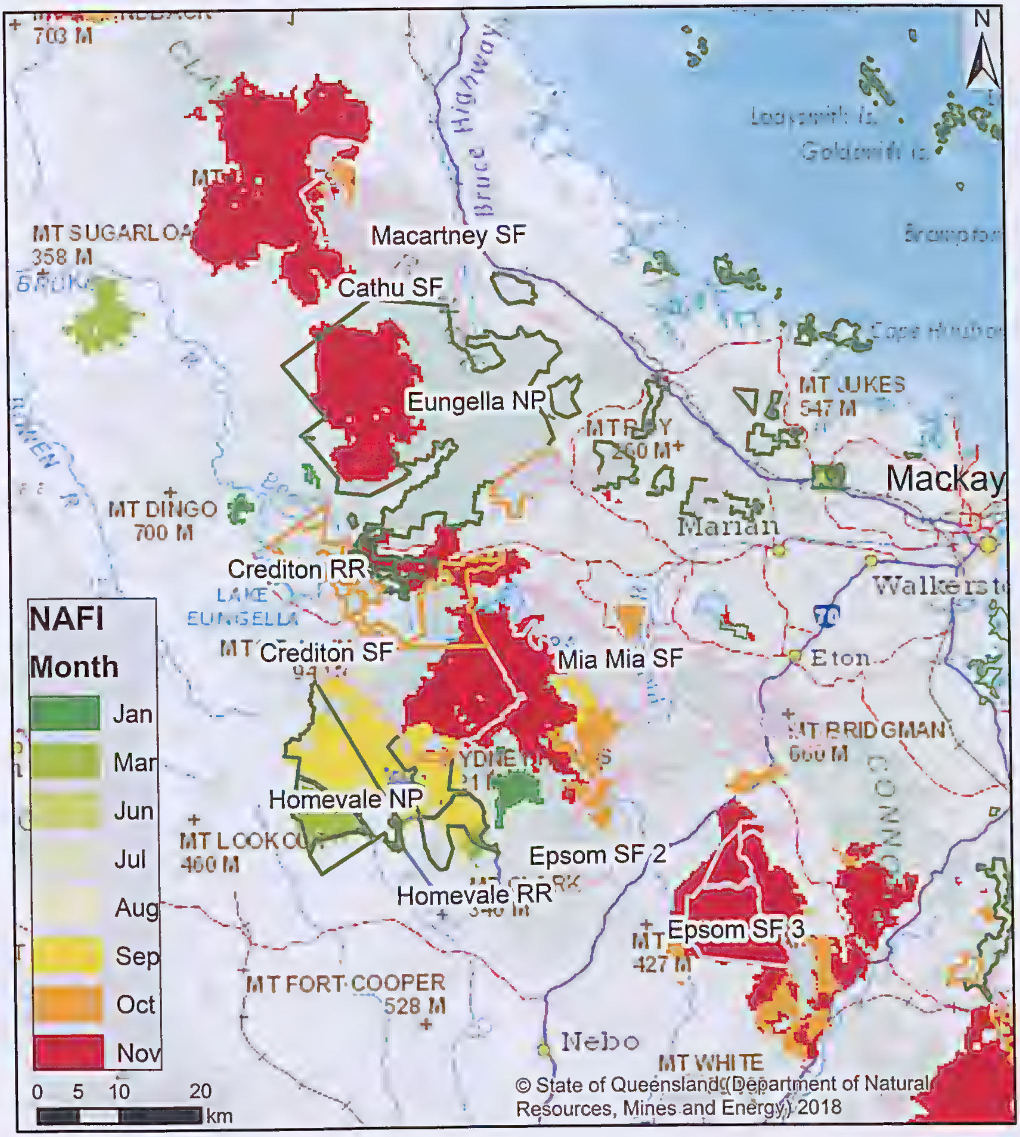

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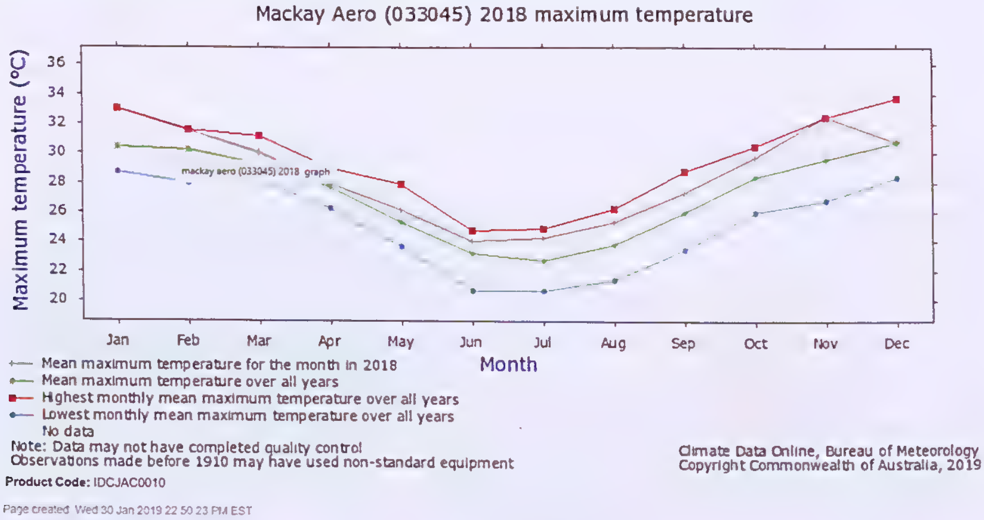
FIGURE 2. Graph of mean maximum temperature, Mackay Aero, for 2018.
Temperatures during 2018 are plotted in grey and are consistently higher than the long-term mean plotted in green, with record temperatures reached in January, February and November 2018.



The assessment on natural values was based on fire extent and severity mapping, distribution of significant natural values with respect to burnt areas, field inspections, published and unpublished information, and expert opinion. The assessment team included local QPWS staff involved with fire suppression efforts and highly knowledgeable of the area, augmented by regional and centrally located natural resource managers and ecologists, a rainforest botanist from the Queensland Herbarium, and regional Queensland Fire and Emergency Service staff. Fieldwork was limited to visual assessments of a range of sites principally in the Eungella-Crediton area, but also included aerial inspections of a broader area. The significant wet season following the fires meant the majority of the field assessments was undertaken in April 2019. The results presented in this paper arose from this assessment.

Fire Extent and Severity Mapping

The Mackay Highlands 2018 wildfire event comprised multiple fires, some burning since August 2018, culminating with a rapid expansion of intense fire in mid–late November that coincided with extreme fire-weather conditions and ending when the wet season broke in early December. North Australia and Rangelands Fire Information (NAFI, 2019) broad-scale fire scar mapping shows the extent of areas burnt by month for 2018 (Figure 1). Early fires (i.e. before August), mostly planned burns, are relatively small in extent. Wildfires became extensive during September, with some reduction in fire activity in October due to rainfall. Fires that started in November, or were already burning, expanded rapidly and show by far the greatest extent of NAFI fire scars for the region in 2018.

We developed finer-scale fire extent and severity mapping as part of the assessment process, using Sentinel 2 satellite imagery that has a resolution of approximately 30 m. Fire severity was determined from pre- and post-fire imagery (for the Homevale area the comparison was 3 September and 8 October, and other areas 3 September and 2 December 2018). A Normalised Burn Ratio (NBR) classification was developed for both pre-fire and post-fire images (Brewer *et al.*, 2005; Miller & Thode, 2007). An NBR difference product (dNBR) was derived from the pre- and post-fire NBR classifications and divided into five severity classes, defined as:

extreme = partial to total defoliation, all understorey burnt to ash (or nearly so);
very high = extensive canopy scorch, partial defoliation, no humus remaining;
high = some canopy scorch, mid stratum completely scorched or nearly so, some humus remains;
moderate = little or no canopy scorch, some elevated fuels scorched, some patchiness, 50% humus remains; or

low = little or no canopy scorch, some elevated fuels scorched, significant patchiness, humus layer remains.

These classes were verified through visual interpretation of the imagery and through aerial and ground-based field assessment.

Other Spatial Datasets

Information on significant species was derived principally from the state's wildlife information system, WildNet (accessed 8 May 2019), which includes plant species locality information held by the Queensland Herbarium. Additional species records were collated from the frog survey and monitoring datasets described by Meyer *et al.* (this issue), the QBERD ecological database managed by the Queensland Herbarium (only records not incorporated within WildNet), and the *Atlas of Living Australia* for *Saproscincus eungellensis* and *Magmellia luteilateralis*. Databases were searched for records with a locational precision of 20,000 m or less that fell within the latitudes of –20.676583 and –21.540028, and longitudes of 148.389472 and 148.811000. This rectangle included an approximate 2 km buffer on the northern, eastern, southern and western extent of the QPWS estate affected by the 2018 fire event. Limited spatial validation of these records was undertaken, with some records rejected due to very poor spatial precision, erroneous georeferences, or because they were duplicates. We scored species according to their dependence on forest ecosystems, and some, such as wading birds, were excluded from further consideration. To help identify those threatened forest species most at risk from wildfire, we classified each according to their known or likely fire sensitivity, or dependence upon fire-sensitive ecosystems (Hardesty, 2005). Spatial datasets on significant species are inherently limited and biased, so we used published and unpublished information, as well as expert opinion to augment the spatial assessment and inform the risk-assessment process. Taxon nomenclature and legislative status is from the Queensland Government's wildlife information system, WildNet, as at May 2019.

Regional Ecosystems (REs) are vegetation communities in a bioregion that are consistently associated with a particular combination of geology, landform and soil. The Queensland Herbarium has mapped REs throughout Queensland, and we used the current version (11.1) for this assessment (Queensland Herbarium, 2019). Many areas have a high spatial diversity of vegetation communities, so at 1:100,000 scale it is not always possible to delineate each vegetation community into homogenous (pure) polygons. Consequently, mapped RE polygons are often heterogeneous, such that a polygon is attributed more than one RE code (e.g. 11.3.2/11.3.25), with the percentage of the area of the polygon occupied by each RE or vegetation recorded (Neldner *et al.*, 2019a). For the purposes of this report the RE assessment utilises RE1 or the dominant RE for each mapped polygon, and does not attempt to take into account the percentage of it within the polygon. The conservation status of REs used here is the 'biodiversity status' (BD status) (Queensland Herbarium, 2019). REs are grouped into higher-level vegetation communities referred to as Broad Vegetation Groups (BVGs) (Neldner *et al.*, 2019b), and we provide some summaries at the 1:2,000,000 and 1:5,000,000 scales, referred to hereafter as 2M and 5M scale.

RESULTS AND DISCUSSION

Burnt Area

Overall, the dNBR classification provided a generally reliable assessment of damage to forest canopy reflecting fire severity as assessed from ground truthing. The mapping must be considered an approximation as the analysis and verification was rapid in nature, but it provides finer-scale mapping of extent and severity than other readily available sources (e.g. NAFI). Over the period August–December 2018, fires affected 12 areas of QPWS managed estate (hereafter referred to as burnt QPWS estates) in the Mackay Highlands, with approximately 71,000 ha or 41% of this estate burnt (Figure 3; Table 1). In excess of 10,000 ha was burnt in each of Crediton SF, Epsom SF 3, Eungella NP and Homevale NP. Eungella NP was affected by several wildfires: the largest started on leasehold land to the north-west, and with a hot, dry and strong north-westerly wind, moved south-east into the NP on the afternoon of 12 November 2018. At least two other fires impacted Eungella NP, both burning up from the Finch Hatton lowlands, one to the north and another to the south of Eungella township.

The twelve QPWS burnt estates fall within the Central Queensland Coast and Brigalow Belt Bioregions and support 49 Regional Ecosystems (REs), of which 37 burnt during the event. Of those that burnt with an extent greater than 10 ha, sixteen have a BD status of 'Endangered' or 'Of concern'. Five Broad Vegetation Groups at 5M scale and thirteen at the 2M scale burnt within the QPWS estate (Table 2). At the 2M scale, within QPWS estate, four Broad Vegetation Groups had more than two-thirds of their extent burnt (Table 2).

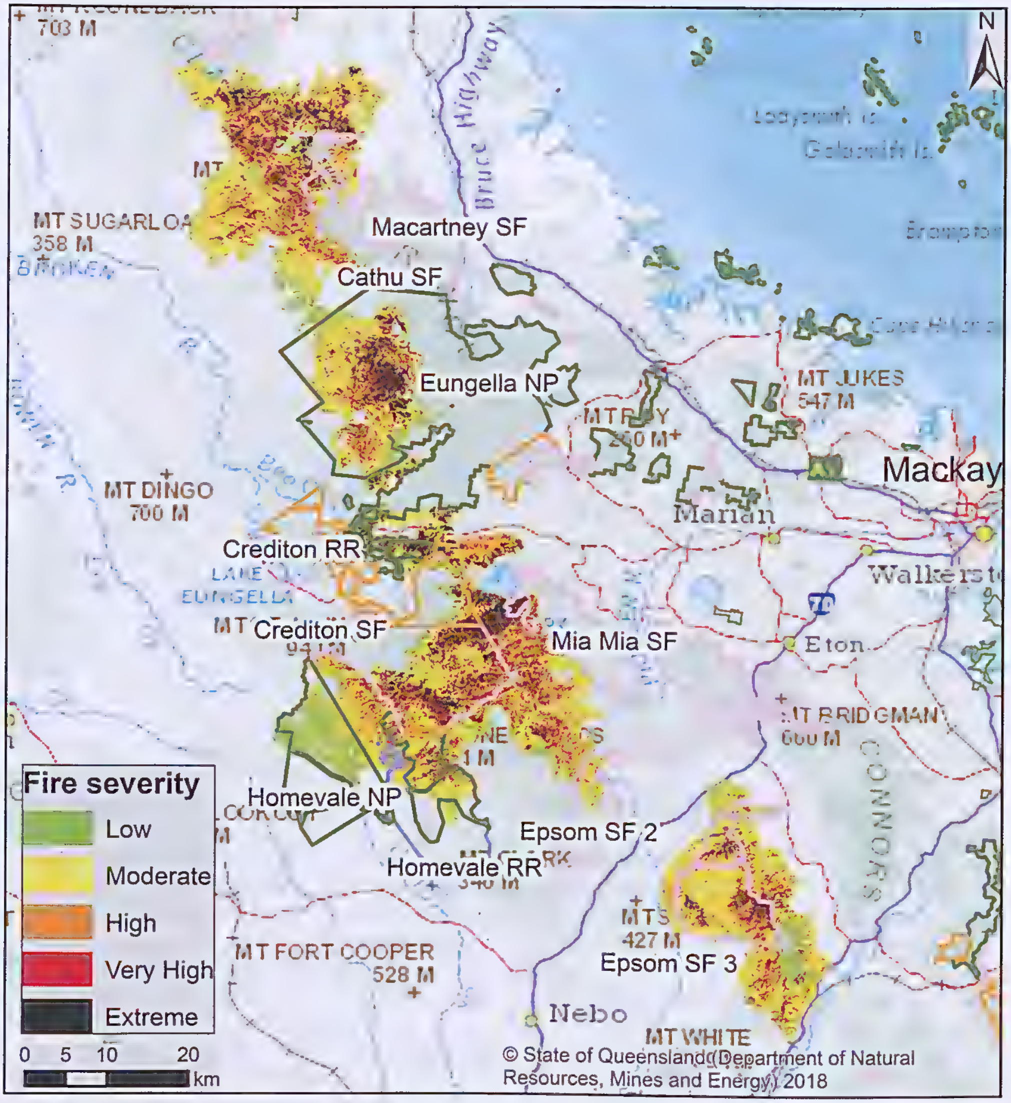


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FIGURE 3. Extent and severity of the Mackay Highlands fire event, August–December 2018, in relation to QPWS estate.

The burnt QPWS estates contain areas of high natural values, in particular the rainforest and scrub communities, wet eucalypt open forests, other eucalypt forest and woodlands and streams. The region is a centre of wildlife endemism, especially within the upland rainforests of the Eungella area. At least 37 threatened or near-threatened species are known or likely to occur within the areas of burnt QPWS estate (Table 3; Figure 4). Of these, seventeen species are fire sensitive (i.e. plant species not dependent on fire for regeneration and killed by low-intensity fire) or are dependent upon fire-sensitive communities (mostly upland rainforests), twelve species are dependent upon fire-prone or fire-adapted communities, and eight species occur within both fire-sensitive and fire-adapted communities. A summary of the extent, severity and observed or inferred effects of the fires within major vegetation communities and their significant species is provided below.

Rainforests and Scrubs

There are fourteen rainforest and scrub REs (mostly evergreen microphyll to notophyll forests) (Group 1, BVG_5M) totalling 58,805 ha within the twelve affected QPWS estates. During the current fire event, 11,217 ha or 19% was burnt, with 3903, 2854, 2138, 1340 and 983 ha at low, moderate, high, very high and extreme severity, respectively (Table 2). Some 4161 ha of rainforest at high altitude (i.e. greater than 800 m asl) was burnt, with approximately a third with high to extreme severity. Rainforests and scrubs are fire sensitive and considered to be generally self-protected, due to their occurrence on rocky substrates or their moist microclimate, particularly the cloud rainforests (mostly above 800 m asl). Field inspections of burnt rainforest in April 2019 showed that even with low flame heights (e.g. 10–20 cm) there was complete loss of leaf litter and ground vegetation (including the seedling bank) and the defoliation or death of vines, shrubs and even very large trees, presumably due to damage to bark and surface roots (Figure 5).

It appears that much of the rainforest that burnt was previously logged. For example, rainforests in the Massey and Pla Creeks catchments were very heavily logged in the 1950–1960s, under the assumption that, post-logging, the remaining areas would be cleared and converted to hoop pine plantations (P. Stanton, *pers. comm.*). The plantations were not established, and the rainforests were left with large canopy gaps that promoted lantana and, more slowly, regrowth of *Alphitonia* and *Acacia* species. Aerial inspection of these areas in early 2018 showed little rainforest canopy recovery and extensive lantana invasion (P. Stanton, *pers. comm.*) which, in combination, likely exacerbated the extent and severity of fire in these areas.

The scrubs and rainforests are core habitat for a range of significant plants and animals, with the cloud rainforests of the Eungella-Crediton area especially important for thirteen species endemic to the Mackay Highlands (Table 3). The significant rainforest plant species are all likely highly fire sensitive, and the loss of individuals from areas of burnt rainforest is almost certain.

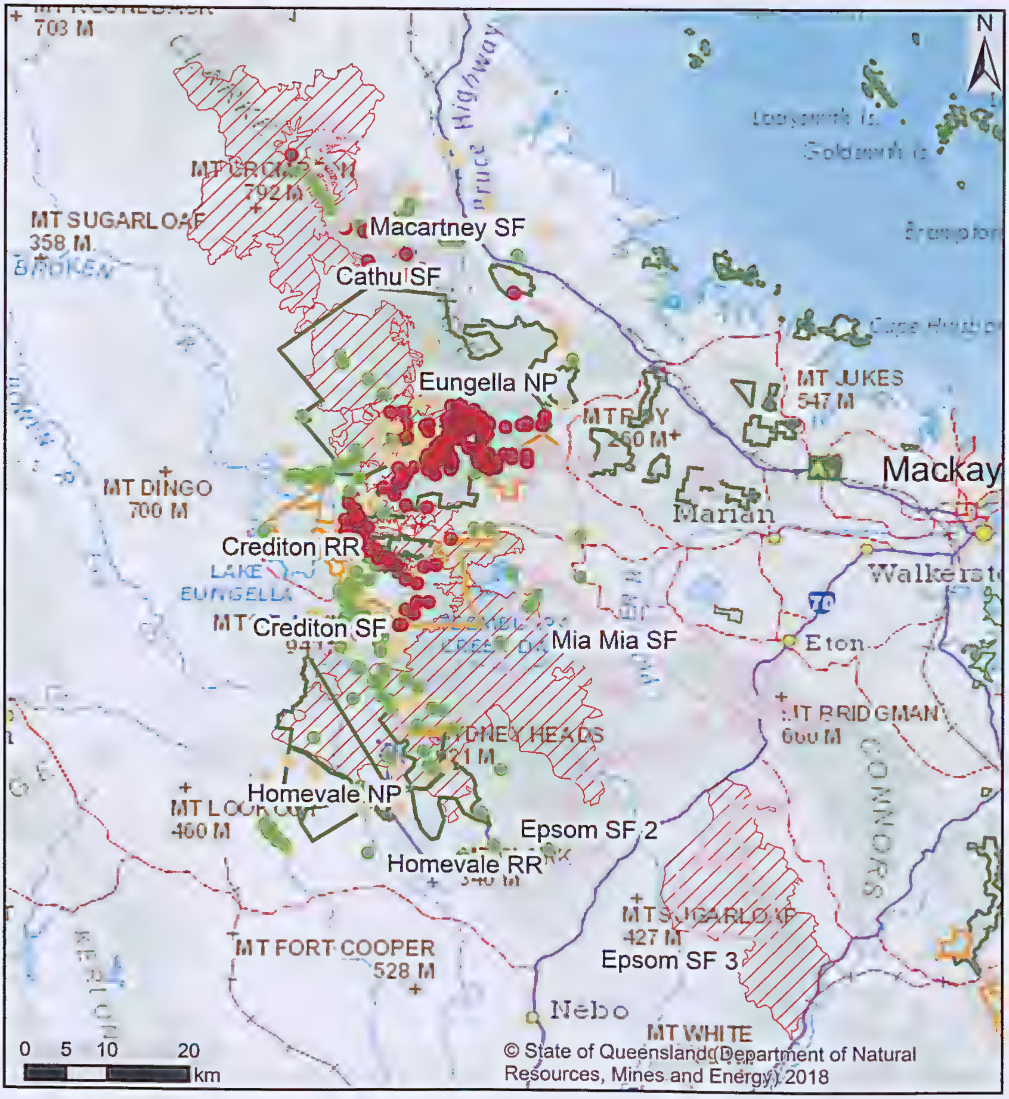
Two terrestrial skinks, *Magmellia luteilateralis* and *Saproscincus eungellensis*, endemic to the upland rainforests of Eungella, are dependent upon large fallen woody debris and leaf litter for shelter and foraging (Wilson, 2015). Direct mortality of these skinks and their prey during the fire is likely, and risk of predation from native and feral predators increased post-fire.

Three species of frogs are endemic to the rainforests of the Eungella-Crediton area: *Rheobatrachus vitellinus*, *Taudactylus eungellensis* and *T. liemi*. *Adelotus brevis* and the regionally significant whirring treefrog, *Litoria revelata*, occur in rainforests as well as other habitats of the Mackay Highlands. The following assessment is based on information from Meyer *et al.* (this issue) and references therein.

TABLE 1. QPWS estate burnt during the 2018 Mackay Highlands fire event.
Estate abbreviations: CP = Conservation Park, FR = Forest Reserve, NP = National Park, RR = Resources Reserve, SF = State Forest.

Estate name	Estate area (ha)	Area of estate burnt (ha)	Percentage of estate burnt
Cathu SF	11,366.0	712.2	6.3
Crediton FR	12,813.0	3,042.1	23.7
Crediton SF	19,562.0	13,408.1	68.5
Epsom SF 1	752.6	514.2	68.3
Epsom SF 2	6,034.0	1,353.6	22.4
Epsom SF 3	10,715.9	10,705.3	99.9
Eungella NP	59,865.4	20,869.0	34.9
Homevale CP	19.5	0.1	0.6
Homevale NP	21,780.6	11,015.0	50.6
Homevale RR	13,300.0	7,355.4	55.3
Macartney SF	7,163.0	1,106.2	15.4
Mia Mia SF	9,000.0	918.7	10.2
Total	**172,371.9**	**70,999.7**	**41.2**

FIGURE 4. Species of conservation significance in the Mackay Highlands area, in relation to QPWS estate and the fire extent (red hatch).
Records of Threatened or Near Threatened species (Table 3) within a bounding rectangle containing the 12 QPWS estates burnt during the Mackay Highlands 2018 fire event. Symbols are: *Fire sensitive* – red dots – species that are fire sensitive (i.e. plants species killed by lower-intensity fire) or are dependent upon fire-sensitive communities; *Fire dependent* – green dots – species dependent upon fire-prone or fire-adapted communities; and *Variable* – orange dots – species that occur within both fire-sensitive and fire-dependent communities.



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Taudactylus eungellensis is strongly associated with permanent streams, with their current core habitat comprising larger, boulder-strewn streams at mid-altitude. Direct mortality from the fires is unlikely, as individuals probably took shelter in water or splash zones. Some loss of streamside vegetation may increase predation risk. This species is diurnally active and often perches in very exposed situations, so likely has adaptations that may limit such susceptibility. The likely greatest impact to *T. eungellensis* is from stream sedimentation/accumulation of burnt debris and short-term changes in water chemistry. An aerial inspection along Massey Creek (April 2019), upstream from about 350 m asl, showed no obvious stream bank instability nor recent build-up of charcoal, silt, sand or gravel, and water was clear. This suggests minimal or transient gross changes to water quality. Tadpoles of *T. eungellensis*, downstream of significant areas of burnt forest, may have experienced significant stress or mortality due to water chemistry changes, which may have reduced recruitment. *Taudactylus liemi* tend to occur in smaller streams, drainage lines and seepages, some of which are more ephemeral and likely dry at the time of the fires. Post-metamorphic frogs shelter in rock piles and leaf litter, including fallen palm fronds. Consequently, this species is likely to have suffered greater direct mortality from the fire. Call perches and breeding sites too are likely to have been directly impacted, with recovery in burnt areas likely to be protracted. Impacts on tadpoles are likely similar to those postulated for *T. eungellensis*. *Adelotus brevis* and *Litoria revelata* are known to forage and shelter well away from streams, so direct mortality from fire is likely. In forests, breeding sites for these species are often pools in bedrock beside streams (e.g. rock holes in cascades or waterfalls, not connected to the stream except during floods) so may not be as susceptible to changes to water chemistry as stream-breeding frogs.

Impacts to frog species of conservation significance are most likely in Massey and Urannah Creeks due to the extent and severity of fire in wet forests in these catchments. However, due to the remoteness of these streams, knowledge of pre-fire distribution and abundance is limited, as is the ability to assess and monitor stream conditions and frog populations post-fire.

In addition to the potential impacts on frogs and skinks outlined above, these species have a diet dependent upon arthropods. Loss of leaf litter, coarse woody debris and standing live vegetation biomass is likely to have greatly reduced arthropod diversity and abundance immediately post-fire.

FIGURE 5. Photographs showing the effects of fire within upland rainforests of the Eungella-Crediton area, ~5 months post-fire (April 2019).

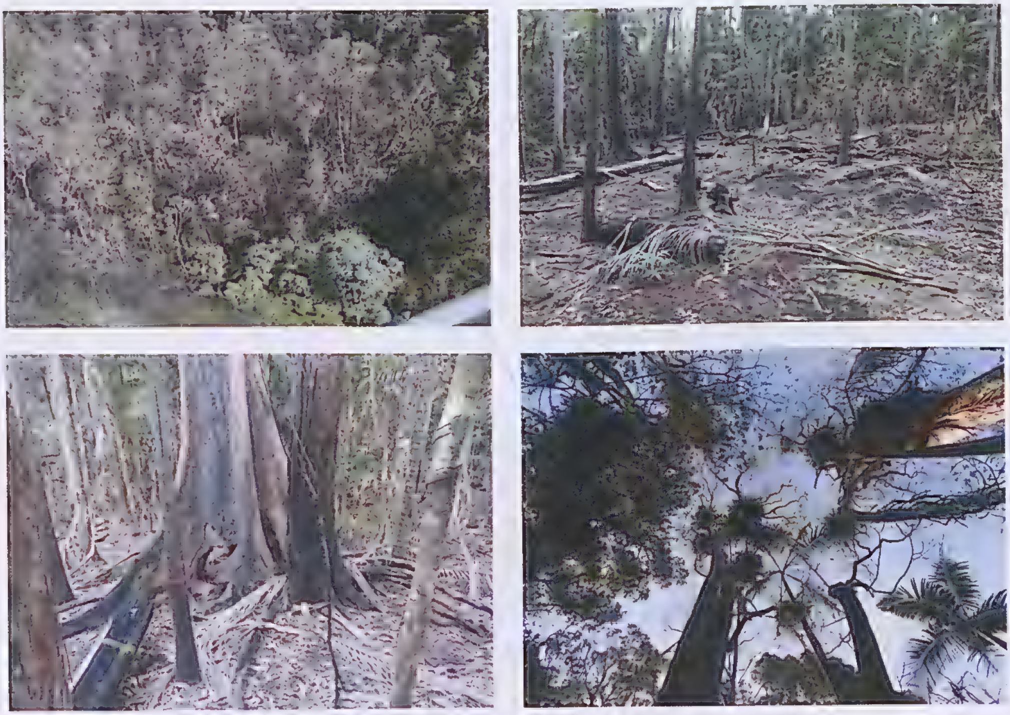


TABLE 2. Area burnt within each fire severity category, by Broad Vegetation Group, within QPWS estate.
Broad Vegetation Groups (BVGs) as described by Neldner *et al.* (2019b), derived from Regional Ecosystem mapping (using RE1). All areas are in hectares. QPWS estate refers to the 12 estates affected by the Mackay Highlands 2018 fire event (see Table 1).
Column headings are: BVG_5M & BVG_2M – descriptions of the BVG at the 1:5,000,000 and 1:2,000,000 scales; Estate – area of BVG_2M within QPWS estate; Burnt – area of BVG_2M burnt on QPWS estate; % burnt – the percentage of BVG_2M within QPWS burnt; Low, Medium, High, Very High and Extreme – area of BVG_2M burnt at these fire severities (see section 3).

BVG_5M	**BVG_2M**	**Estate**	**Burnt**	**% burnt**	**Low**	**Moderate**	**High**	**Very High**	**Extreme**
Non-remnant.	Non-remnant.	4,732.50	1354.55	28.62	724.35	252.42	90.84	71.96	214.97
Rainforests, scrubs.	Complex to simple, semi-deciduous mesophyll to notophyll vine forest, sometimes with *Araucaria cunninghamii* (hoop pine).	813.24	783.55	96.35	655.75	52.85	28.75	20.98	25.21
	Notophyll and mesophyll vine forest with feather or fan palms on alluvia, along streamlines and in swamps on ranges or within coastal sandmasses.	4.27	1.40	32.84	0.00	0.18	0.15	0.39	0.68
	Notophyll to microphyll vine forests, frequently with *Araucaria* spp. or *Agathis* spp. (kauri pines)	50,658.15	9,480.96	18.72	2,837.57	2,578.76	1,953.45	1,208.60	902.58
	Notophyll vine forest and microphyll fern forest to thicket on high peaks and plateaus.	3,215.06	59.80	1.86	14.38	15.52	16.97	9.48	3.45
	Semi-evergreen to deciduous microphyll vine thicket.	4,114.23	892.14	21.68	394.85	206.64	138.70	100.49	51.45
Wet eucalypt open forests.	Wet eucalypt tall open forest on uplands and alluvia.	4,509.63	3,188.07	70.69	297.01	684.73	895.24	598.78	712.31
Eastern eucalypt woodlands to open forests.	Moist to dry eucalypt open forests to woodlands usually on coastal lowlands and ranges.	30,486.44	12,198.94	40.01	958.98	1,555.56	2,909.61	3,664.79	3,110.00
	Corymbia citriodora (spotted gum) dominated open forests to woodlands on undulating to hilly terrain.	29,876.39	18,464.26	61.80	1,945.35	4,657.22	6,054.67	3,821.68	1,985.35
	Moist to dry eucalypt open forests to woodlands mainly on basalt areas (land zone 8).	1,686.00	1,442.54	85.56	1,222.41	212.28	7.08	0.66	0.11

BVG_5M	BVG_2M	Estate	Burnt	% burnt	Low	Moderate	High	Very High	Extreme
Eastern eucalypt woodlands to open forests (*cont.*)	Dry to moist eucalypt woodlands and open forests, mainly on undulating to hilly terrain of mainly metamorphic and acid igneous rocks (land zones 11 and 12).	32,813.92	19,354.85	58.98	6,556.05	6,949.17	4,472.62	1,139.97	237.04
Eucalypt open forests to woodlands on floodplains.	*Eucalyptus* spp. dominated open forest and woodlands drainage lines and alluvial plains.	2,373.79	1,854.46	78.12	209.67	873.81	664.33	94.22	12.43
Eucalypt dry woodlands on inland depositional plains.	*Eucalyptus populnea* (poplar box) or *E. melanophloia* (silver-leaved ironbark) (or *E. whitei* (White's ironbark)) dry woodlands to open woodlands on sandplains or depositional plains.	3,162.01	610.54	19.31	451.89	140.25	18.04	0.35	0.00
	Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains.	27.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Melaleuca open woodlands on depositional plains.	*Melaleuca* spp. on seasonally inundated open forests and woodlands of lowland coastal swamps and fringing lines. (palustrine wetlands).	508.72	163.21	32.08	101.16	28.60	20.36	8.96	4.13
Other acacia dominated open forests, woodlands and shrublands.	*Acacia harpophylla* (brigalow) sometimes with *Casuarina cristata* (belah) open forests to woodlands on heavy clay soils.	538.23	18.56	3.45	8.28	8.68	1.60	0.00	0.00
Other coastal communities or heaths.	Open forests to open woodlands in coastal locations. Dominant species such as *Casuarina* spp., *Corymbia* spp., *Allocasuarina* spp. (she-oak), *Acacia* spp., *Lophostemon suaveolens* (swamp box), *Asteromyrtus* spp., *Neofabricia myrtifolia*.	2,459.91	1,131.39	45.99	67.26	162.11	316.34	290.06	295.62

TABLE 3. Threatened, Near Threatened or endemic forest fauna and flora species of the Mackay Highlands. NCA (*Nature Conservation Act 1992*) and EPBC (*Environment Protection and Biodiversity Conservation Act 1999*) statuses are: EX = extinct, E = endangered, V = vulnerable, NT = near threatened, LC = least concern. Rf & scrub = rainforest and scrubs, Euc = eucalyptus woodlands and forests; with X = the habitat is important for the species in the Mackay Highlands region, End = the species is endemic to the region, and Brig = species occurs in brigalow communities. Eungella spiny crayfish is listed as Critically Endangered on the IUCN Red List.

Group	Common name	Scientific name	NCA	EPBC	Rf & scrub	Euc
Animals						
crustaceans	Eungella spiny cray	*Euastacus eungella*			End	
insects	pale imperial hairstreak	*Jalmenus eubulus*	V		Brig	
amphibians	tusked frog	*Adelotus brevis*	V		X	X
amphibians	northern gastric brooding frog	*Rheobatrachus vitellinus*	E	EX	End	
amphibians	Eungella dayfrog	*Taudactylus eungellensis*	E	E	End	
amphibians	Eungella tinkerfrog	*Taudactylus liemi*	NT		End	
birds	red goshawk	*Erythrotriorchis radiatus*	E	V	X	X
birds	glossy black-cockatoo (northern)	*Calyptorhynchus lathami erebus*	V			X
birds	squatter pigeon (southern)	*Geophaps scripta scripta*	V	V		X
birds	Eungella honeyeater	*Bolemoreus hindwoodi*	V		End	End
birds	powerful owl	*Ninox strenua*	V			X
mammals	northern quoll	*Dasyurus hallucatus*	LC	E	X	X
mammals	ghost bat	*Macroderma gigas*	E	V	X	X
mammals	koala	*Phascolarctos cinereus*	V	V		X
mammals	northern greater glider	*Petauroides volans minor*	V	V		X
mammals	grey-headed flying-fox	*Pteropus poliocephalus*	LC	V	X	X
reptiles	common death adder	*Acanthophis antarcticus*	V			X
reptiles	ornamental snake	*Denisonia maculata*	V	V	Brig	
reptiles	orange-speckled forest-skink	*Magmellia luteilateralis*	V		End	
reptiles	peppered-belly broad-tailed gecko	*Phyllurus nepthys*	LC		End	
reptiles	Eungella shadeskink	*Saproscincus eungellensis*	V		End	
Plants						
Aspleniaceae		*Asplenium normale*	V		End	
Asteraceae		*Ozothamnus eriocephalus*	V	V		X
Dryopteridaceae		*Dryopteris sparsa*	V		X	
Dryopteridaceae		*Elaphoglossum callifolium*	NT		X	
Euphorbiaceae	Mt. Coolum bertya	*Bertya sharpeana*	NT			X
Euphorbiaceae		*Omphalea celata*	V	V	X	
Euphorbiaceae		*Trigonostemon inopinatus*	V		X	
Lamiaceae		*Plectranthus graniticola*	V		End	End
Lycopodiaceae		*Phlegmariurus tetrastichoides*	V	V	X	

Group	Common name	Scientific name	NCA	EPBC	Rf & scrub	Euc
Plants (*cont.*)						
Lycopodiaceae		*Phlegmariurus varius*	V		X	
Myrtaceae	black ironbox	*Eucalyptus raveretiana*	LC	V		X
Myrtaceae		*Kunzea sericothrix*	E			End
Myrtaceae		*Sannantha papillosa*	E			X
Orchidaceae		*Chiloglottis longiclavata*	NT			X
Poaceae		*Dichanthium setosum*	LC	V	X	X
Rutaceae		*Acronychia eungellensis*	NT		End	
Sapindaceae		*Sarcotoechia heterophylla*	NT		End	
Solanaceae		*Solanum francisii*	LC		End	

The Eungella honeyeater (*Bolemoreus hindwoodi*) is also endemic to the region. Higgins *et al.* (2001) summarise the scant published information on this species. Its habitat is predominantly upland rainforests, but it also utilises eucalypt forests and woodlands (possibly more so in winter). The few breeding records are from upland rainforests in spring. Its diet consists of nectar, fruit and insects. Impacts from fires on *B. hindwoodi* are likely to be significant and long term in areas of burnt upland rainforests. Even at low severity, fires killed extensive areas of rainforest climbers of the genus *Freycinetia*, an important food source for *B. hindwoodi*. The species will also be affected where fires burnt at higher severity in eucalypt communities of the Eungella-Crediton area. Impacts will occur over a greater area, but are likely to be much shorter lived as these communities are fire adapted.

Other Fire-sensitive Communities

We estimate that 19 ha of endangered (BD status) brigalow community burnt within QPWS estate (Homevale RR), mostly at low to moderate severity. This vegetation is fire sensitive, although the dominant species – brigalow (*Acacia harpophylla*) – typically resprouts from rootstock, and occurs in lower-altitude, drier areas in the western part of the study area. The pale imperial hairstreak (*Jalmenus eubulus*) is dependent upon brigalow-dominated, old-growth open forests and woodlands (Eastwood *et al.*, 2008). This butterfly has been recorded from the region but is patchily distributed, and it is not known whether a population occurred within the burnt area. If present, however, impacts are likely significant. The ornamental snake *Denisonia maculata* also occurs in brigalow communities and has been recorded from the study area, so may have been impacted by the fires.

Wet Eucalypt Open Forests

There are two significant wet eucalypt open forest (Group 2 BVG_5M) REs (*Eucalyptus grandis* and *E. montivaga* communities), with a limited distribution in the higher-elevation western ridges and slopes of the Clarke Range. Both are naturally restricted in occurrence, are only represented in protected areas within Eungella NP and Crediton FR, and have a BD status 'Of concern'. These communities provide important habitat for several threatened species (see discussion below) or important disjunct populations.

RE 8.12.4, *E. grandis* open forests of wet uplands on Mesozoic to Proterozoic igneous rocks (predominantly granite), is threatened by the development of a rainforest understorey and requires fire to prevent this occurring (Bradford, 2018; Queensland Herbarium, 2019). Most areas have been logged, with resulting reduction in size and form of canopy trees. Logging, grazing and, potentially, past fire management have exacerbated weed invasion, with lantana (*Lantana camara*) a particular concern. During the current fire event, 2281 ha (69% of the total extent of this RE within QPWS estate) was burnt, with 272, 486, 615, 449 and 459 ha burnt at low, moderate, high, very high and extreme severity, respectively. During field inspections, we observed mixed-age stands of *E. grandis* in several areas, with recruitment presumably from past fire or logging events, and germination from the current fire event. Defoliation or death of rainforest and lantana shrubby understorey was widespread within the burnt areas visited, with significant fire incursion into some adjacent rainforest stands. The ecological outcomes for this community are likely mixed. Of concern is the extent of fire within this community, with a majority of areas within QPWS estate burnt. However, fire severity was mixed, with a significant area (1522 ha or 46% of the total extent of the RE within QPWS estate) of high to extreme severity, likely to meet the ecological requirements of this community where affected by rainforest invasion. The reduction in lantana cover is likely short lived, and the fire may in fact provide opportunities for further lantana invasion. High-biomass grasses do not appear to be a significant issue for this community at present.

Some 908 ha (74% of the total extent of this RE within QPWS estate) of RE 8.12.8, *E. montivaga* open forest on plateaus and ridges of high ranges on Mesozoic to Proterozoic igneous rocks, was burnt. Again, fire intensity varied, with 25, 198, 280, 150 and 253 ha burnt at low, moderate, high, very high and extreme severity, respectively. The recommended fire interval for this community is 10+ years with expected intensity high (Queensland Herbarium, 2019). This community tends to grow on exposed ridges with shallow, relatively infertile soils, so rainforest invasion and weeds are not as significant an issue as with the *E. grandis* community. Ecologically, the current fire event is unlikely to have significantly impacted this community.

Other Eucalypt Forests and Woodlands

Large tracts of drier eucalypt open forests and woodlands (Groups 3 & 4, BVG_5M) within the QPWS estate were burnt during the event (Table 2) – about 54,000 ha, or 54% of its extent within the QPWS estate. These vegetation communities are fire adapted and fire prone. Nevertheless, the extent of the fire, as well as significant areas (28,192 ha) with high to extreme severity, are cause for concern.

These eucalypt communities provide important habitat for many threatened or near-threatened species (Table 3). The endangered shrub *Kunzea sericothrix* is only known from a single location, on Dicks Tableland, within the burnt area. *Sannantha papillosa*, another endangered shrub, is also recorded from the burnt area. Both these shrubs occur within highly fire-prone environments and are likely to be well adapted to fire, but their susceptibility to repeated high-intensity fires is not known. These and some other significant plant species grow in skeletal soils on bedrock, which may have afforded protection from fire for some individuals.

The impact of the fire on significant fauna species of the eucalypt communities is difficult to ascertain, as it will vary depending on their distribution, abundance and ecology within the Mackay Highlands area. The Clarke-Connors Range area supports significant populations of koalas (*Phascolarctos cinereus*) (Melzer *et al.*, 2018) and northern quolls (*Dasyurus hallucatus*) (Woinarski *et al.*, 2008), and specific information on their likely response to extensive and/or intense fire is provided in the reports (*op. cit.*) and sources cited within them. A brief synthesis of this information is provided below.

Dasyurus hallucatus is a medium-sized, predominantly nocturnal, marsupial carnivore, with insects forming a large proportion of the diet. They breed once a year, with young born mid-year. Young are carried by the mother for 8–10 weeks, then left in a den until they are about five months old. Den sites include rocky outcrops, tree hollows, hollow logs, termite mounds and goanna burrows. As the fires coincided with the period when young are in dens, direct mortality may well have been high given the extent and severity of the fire. Recent studies have suggested that *D. hallucatus* are vulnerable to extensive frequent fires. In a detailed radio-tracking study, the main cause of *D. hallucatus* mortality was predation following extensive fire, due to reduced groundcover. In previous studies in central Queensland (including sites within the current burnt area), there was a clear pattern wherein quolls were absent, or in very low numbers, at sites where fire had been extensive; and most abundant where time since fire was longer, or burnt areas were smaller or patchier (such as areas where large boulders broke up the fire). Post-fire predation is likely exacerbated where cats and foxes are present. A key management recommendation of Woinarski *et al.* (2008) was that fire frequency should be low, and burns patchy and of relatively low intensity. The Mackay Highlands 2018 fire event, in contrast, was extensive and of relatively high intensity.

The Clarke-Connors Range is a significant refuge for *P. cinereus* in Queensland, with inappropriate fire considered a critical threatening process in this region. The risks to *P. cinereus*, and to their habitat, are high if fires occur under unsuitable conditions, such as during severe fire weather or high fuel loads that result in high-intensity fires with associated canopy loss and death of individuals. Canopy scorching results in the loss of food and water for *P. cinereus*. Accordingly, *P. cinereus* were likely significantly impacted during and after the fire event. In addition, the extreme heatwave and preceding low rainfall in spring 2018 are likely to have exacerbated fire impact, forcing individuals to seek refuge in creek beds, tree hollows or at the base of trees, making them more susceptible to the fire and predation. The stress of the fires and heatwave may also increase disease susceptibility (Dr Alistair Melzer, *pers. comm.*). The scrubs (vine thickets/rainforests) adjacent to eucalypt forests are an important refuge for *P. cinereus*, especially during heatwaves: the fires significantly affected some of these communities (Table 2).

Risk Assessment

The QPWS post-fire risk assessment produced fine-scale mapping of fire extent and severity. When used in conjunction with collated information on significant ecosystems and species from local and expert knowledge and published and unpublished literature, this mapping provides a sound basis for assessing potential impacts of the fire to inform short- to long-term recovery planning.

The Mackay Highlands 2018 fire event burnt 71,000 ha of twelve areas of QPWS estate, within various fire-sensitive and fire-adapted vegetation communities at a range of burn severities. Our field observations suggest that even at low fire severity, ecological impacts on upland rainforests are severe and likely long lived. Within the fire-adapted eucalypt communities, some impacts are likely high due to the extent of the burnt area, as well as the proportion of the area burnt at higher fire severities. Past disturbances, such as clearing, grazing, logging and cyclones, preceding rainfall deficiencies with protracted low humidity and high temperatures, including an extreme heatwave, confound assessment of the ecological impacts of the fires. Likewise, potential, or time to, recovery is dependent upon many factors including the extent and severity of future fires, weather, and interactions with pest plants and animals and diseases. Conditions conducive to invasion by pest plants, in particular high-biomass grasses and lantana, were created by the fires in some areas. Establishment of such weed species can impede regeneration directly through competition and, indirectly, by increasing the frequency and severity of future fires. The key ecological outcomes from the fire event are summarised below.

Eucalypt communities are widespread in the QPWS estate of the Mackay Highlands. They are fire-dependent communities, but their ecological fire requirements vary considerably across the study area (Queensland Herbarium, 2019). Lower, drier forests and woodlands with grassy understoreys require fires at greater frequency than wetter, upland communities. Forests with shrubby understoreys tend to require longer fire intervals but burn more intensely. In some wet eucalypt open forests, periodic fire is required to prevent ecosystem transition to rainforest. Accordingly, ecological outcomes will vary with ecosystem type, as well as the extent and severity of the current and past fire events. Although extent mapping of past fires is available for the QPWS estate, fine-scale fire severity mapping is not. Fire frequency and age class assessments were beyond the scope of the current work but are important for informing ongoing fire management of the QPWS estate. Our assessment of ecological outcomes here is restricted to the current fire event.

Our principal concerns for eucalypt communities lie with the vast extent of the 2018 fires and the area burnt at higher levels of severity. Specific information on the ecology of *Phascolarctos cinereus* and *Dasyurus hallucatus* in the Mackay Highlands strongly suggests that the widespread, high-severity fire, coupled with the preceding rainfall deficit and extreme high temperatures, is likely to have had serious impacts. Similar impacts are likely for a range of other fauna in this area for which we lack detailed ecological knowledge. In contrast, at the wetter end of the eucalypt forest spectrum, the 2018 event is likely, in places, to have met ecological requirements. For example, in areas of the 'Of concern' *Eucalyptus grandis* community, the fire appears to have killed rainforest understorey species, opened up the forest structure and, as we observed, initiated recruitment of *E. grandis* (see Stanton *et al.*, 2014; Russel & Franklin, 2018). However, recovery of, or invasion by lantana post-fire in this community may outcompete *E. grandis* seedlings and alter subsequent fire extent and severity. At the landscape scale, the 2018 wildfire event likely promoted some pest plants, particularly invasive, high-biomass grasses, which will likely lead to susceptibility to higher-severity fires in the future. Where weeds are not a concern, fire-adapted plant species will regenerate through seedlings (sometimes *en masse*) or through resprouting, and, for many, fires are critical to their ecology.

Rainforests and scrubs are fire sensitive. Drier rainforest types tend to be more resilient to low-intensity fire, as they often occur adjacent to fire-adapted eucalypt communities and have some adaptive traits to cope with low-severity fire. In contrast, upland rainforests, particularly cloud rainforests, are very rarely dry enough to burn and lack appropriate adaptive traits, so are highly sensitive to fire. Uhl *et al.* (1998) demonstrated that tropical rainforests have structural characteristics that confer resistance to fire. Closed canopies trap moisture and maintain an understorey with consistently high relative humidity that results in leaf litter and other fuels remaining moist between rainfall events. In their study in Venezuela, Uhl *et al.* (1998) estimated that the understorey only dried to a point where combustion was possible less than one day per year on average. In cloud rainforests, like those in the Eungella-Crediton area, such conditions are likely to be even rarer.

We found that even very low flame heights in rainforests and scrubs resulted in the immediate complete loss of leaf litter and the ground stratum, and widespread tree and shrub defoliation or death, immediately or within the months following the fires. Some resprouting of trees and shrubs was evident five months post-fire in areas with low burn severity. In a post-fire study in lowland tropical rainforest in Queensland's Wet Tropics, Marrinan *et al.* (2005) showed most species had some ability to resprout, but a small, potentially significant group of species was less capable than others. Such differences in responses could lead to longer-term changes in rainforest floristics and structure. Many fire-damaged trees and shrubs, however, are likely to succumb to fungal infection, insect attack, exposure and wind throw (House *et al.*, 1998). Long-term monitoring is needed to assess fully tree and shrub mortality. Where fire severity was high to extreme, complete tree and shrub mortality is likely, as is total loss of seed and seedling banks. In such circumstances, recovery will be dependent upon immigration of propagules from unburnt rainforest. Rainforest species differ widely in fruiting phenology, dispersal ability and germination requirements. Proximity to unburnt patches will influence rate of recovery, with recovery of the interior areas of large burnt patches likely only in the very long term (100s of years).

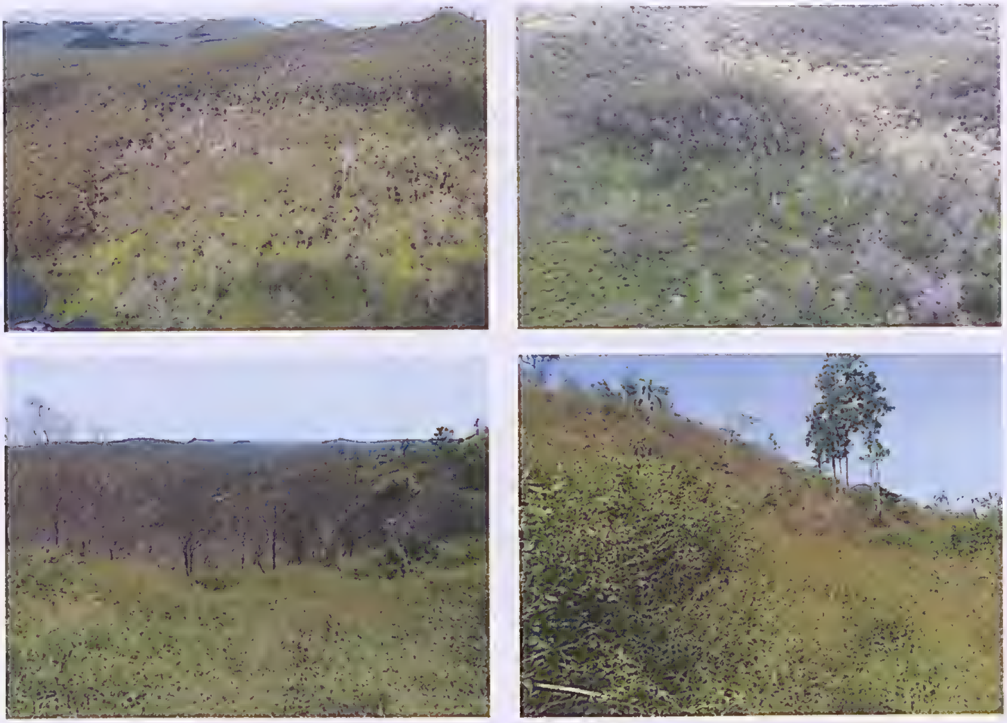
Invasion of pest plants, such as lantana or high-biomass grasses, which are prevalent in the Mackay Highlands, will impede recovery. Higher fire severities were particularly evident in rainforests previously disturbed by clearing, logging or road construction, especially where weeds were present. These disturbances open up rainforest, alter microclimate (to become drier and warmer), and lead to changes in floristics (e.g. presence/dominance of *Alphitonia* and *Acacia* species, lantana), which in combination appear to increase flammability.

Future fires within recovering burnt rainforest, particularly where fire-adapted weeds establish, will result in the loss of these communities – as occurred in a patch of complex notophyll vine forest in the Crediton area that burnt in November 1992 (House *et al.*, 1998) and November 2018. Logging before the 1992 fire created a discontinuous canopy in places and facilitated the establishment of lantana. An area of 520 ha of the rainforest burnt under extreme fire-weather conditions in 1992, with the majority having greater than 50% crown death. House *et al.* (1998) studied the patch for four years and reported varying levels of recovery dependent upon past logging and fire intensity. They also noted an increasing dominance of lantana. Without further fire, they predicted recovery might take a century or more. The fire in 2018 occurred under severe to extreme conditions and resulted in almost complete replacement of the rainforest with weeds (e.g. *Desmodium uncinatum*, *Lantana camara*, *Parthenium hysterophorus*, *Themeda quadrivalvis*, *Solanum* spp.) apart from some common rainforest pioneer species (Figure 6).

The response of significant fauna species dependent upon rainforest will vary according to their ecology. Loss of ground cover will have significant impacts on species dependent upon it for shelter or foraging (e.g. the vulnerable skinks), or on species with a diet reliant upon arthropods that depend upon forest litter or understorey plants (e.g. potentially stream-breeding frogs). Rainforests burnt at high to extreme fire severity are unlikely to support populations of significant fauna species in the short to medium term. Species dependent upon streams, such as threatened frogs and the Eungella spiny cray (*Euastacus eungella*), may have been subjected to changes in water chemistry and quality following the fire, but the magnitude and extent of these changes (spatially and temporally) or the effect on these species are not known. Some rainforest flora species may benefit from the fires. For example, members of the genus *Solanum* often respond to disturbance, so the endemic *S. francisii* may proliferate in the short to medium term.

In all burnt communities, the risk of predation rises immediately post-fire, due to loss of cover, potentially exacerbating impacts from feral predators such as cats and foxes. McGregor *et al.* (2016) have shown that, in northern Australia, cats will move long distances outside of their home range to forage in recently severely burnt areas, presumably to take advantage of displaced fauna and more open foraging areas.

FIGURE 6. Loss of a rainforest patch in Crediton State Forest due to fires in 1992 and 2018.



CONCLUSION

The Mackay Highlands 2018 fire event burnt extensive areas of fire-adapted and fire-sensitive vegetation communities, some during extreme fire weather. Our assessment has identified a number of likely significant medium- to long-term impacts on the natural values of the region. In particular, recovery of burnt fire-sensitive communities, especially upland rainforests, will take decades to centuries. This event provides an important opportunity to assess in detail the ecological effects of fire to inform conservation management of these fire-sensitive communities. With the predicted increases in the frequency, magnitude and duration of heatwaves (QFES, 2019), fires will become more common within mesic vegetation communities hitherto considered self-protected from fire.

ACKNOWLEDGEMENTS

Many QPWS staff were involved directly with efforts to suppress the Mackay Highlands fires and in the post-fire assessments of fire extent, severity and impacts on values. In particular, we thank Eddie Adams, John Atkinson, Scott Brook, Ben Hall, Rowan Heymink, Bill Lennox, Marty McLaughlin, Adrian Matthews and Jamie Mussig. Michael Koch from QFES Rural Fire Service also assisted with the post-fire assessment, particularly in relation to the rainforest patch in Crediton SF burnt previously in 1992. Peter Stanton (Assistant District Forester Mackay 1963–1967, subsequently QPWS until 1997) provided observations on past logging and fire in the area. Rhonda Melzer, Marty McLaughlin (both QPWS) and Roger Kitching (editor) provided valuable feedback on the manuscript. The authors wish to thank DES library services for their assistance with literature searches.

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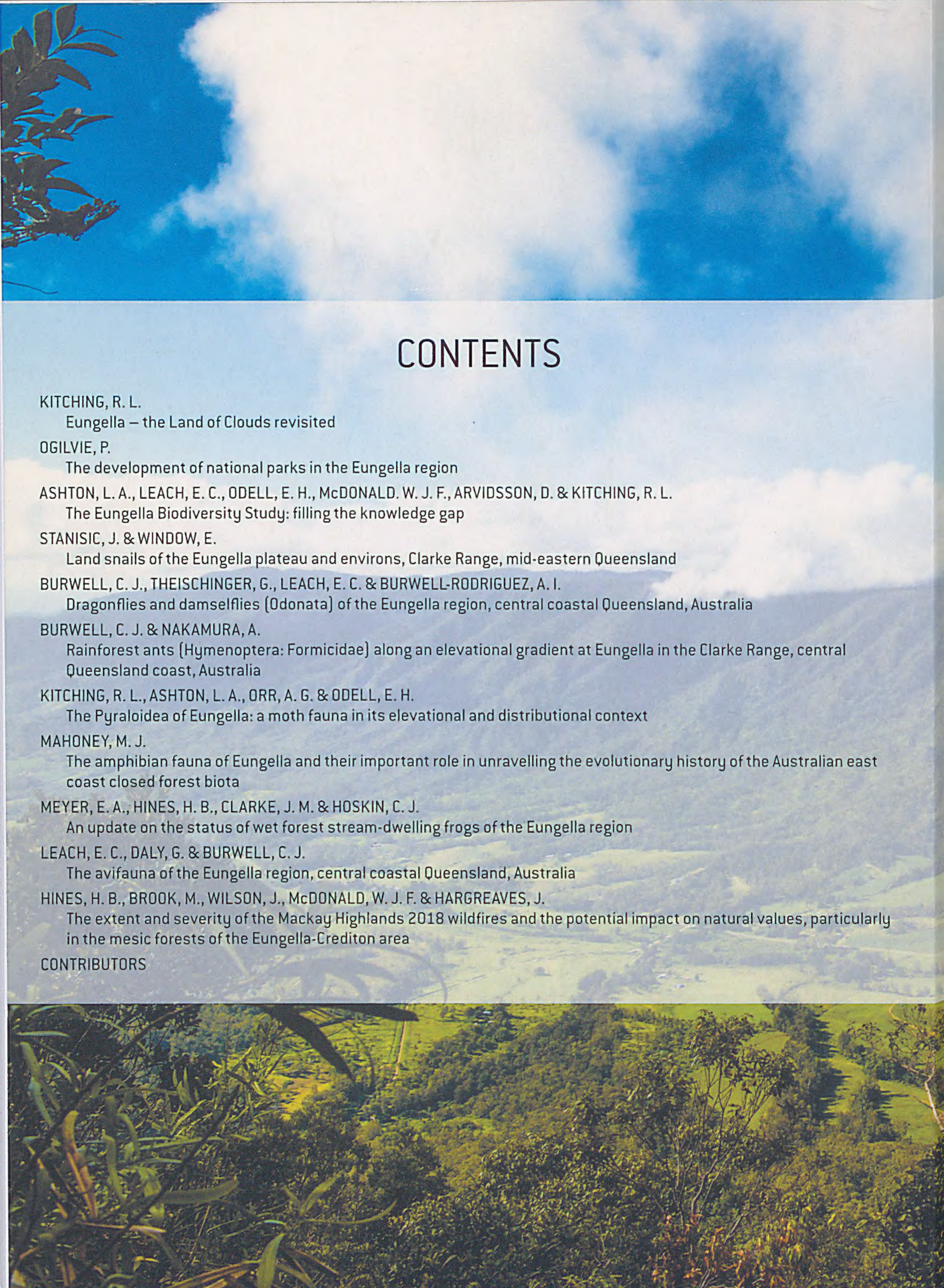

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